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THE STUDY OF OPTIMAL MODEL REFERENCE ADAPTIVE. CONTROL OF A CONTINUOUS STIRRED TANK REACTOR USING AN ON-LINE HYBRID COMPUTER

bу

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SUMMARY

A general algorithm and theory of optimal model reference adaptive control (OMRAC) for processes with n-state variables has been developed, and its need was strongly supported by the results of a comprehensive literature survey and analysis. The theory has been tested on a fully and a partially simulated continuous stirred tank reactor using two state variables and, in both cases, has given satisfactory results. A hybrid computer has been used for both operations, and in the partially simulated case a well-stirred vessel with its auxiliary heat transfer equipment was used as the real plant item.

OMRAC is a combination of two schemes, viz. the optimal model reference (OMR) scheme and the optimal adaptive control (ÖAC) scheme. The optimal model reference scheme is generated by an optimal control law, $m^*(t)$ with constant parameters to generate optimal state variable profiles or trajectories, $\theta^r(t)$. The optimal adaptive control scheme is generated by a modified optimal control law, $U^*(t)$ with constant parameters to minimise the difference between the optimal state variable profiles, $\theta^r(t)$, and the real process variables, $\theta(t)$, in the presence of unmeasurable changing parameters.

The theoretical development of OMRAC has been confirmed for a range of possible operating conditions both in complete simulation tests and also in experimental on-line operation of the partially simulated system. The operation of the on-line hybrid computer control system was successful and gave a reliable performance

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provided care was taken in the computer programming and precautions for linear interface design and output response sensitivity were implemented.

DEDICATION

to

My Mother

and

My Wife

- iii -

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INDEX

			Page
Summary		. ≠ 1	i
Chapter	1.	Introduction	1
Chapter	2.	Literature Survey on Adaptive Control	5
23*	2.1.	Basic concept, definition and classifications	6
	2.2.	General brief review of adaptive control system from known surveys and text books	11
	2.3.	General survey of adaptive control system from current papers excluding Chemical Engineering	17
	2.4.	General survey of adaptive control system in Chemical Engineering	26
	2.5.	Summary of the current literature on adaptive control system:	32
		 A general summary of the current literature on adaptive control system (Table 2.1) 	32
(*		2. A general summary of the current literature on model reference adaptive control system (Table 2.2)	33
	2.6.	Discussion	39
PART I.	.THEOF	RETICAL AND COMPLETE SIMULATION WORK	
Chapter	3.	Theoretical development of general	
		scheme for Optimal Model Reference Adaptive Control (OMRAC)	41
	3.1.	General algorithm and theory of OMRAC	41
	3.2.	Optimal control system	44
	3.3.	Optimal model reference (OMR) scheme	46
	3.4.	Optimal adaptive control (OAC) scheme	49
	8	3.4.1. Modified optimal control law by "Optimal P"	49
		3.4.2. Modified optimal control law by "Optimal P + I"	55

		1	Modified optimal control law by "Optimal P + I + D" Discussion	58 61
		2.4.4.	Discussion	01
Chapter	4.		ical derivation of the OMR scheme inuous stirred tank reactor	62
¥	4.1.	Assumpti	ons for the derivations	62
	4.2.	Process	mathematical model	63
	4.3.	Optimal o	control system	66
	4.4.	Considera	ation of constraints	71
	4.5.		ation of the coefficients: , α_{23} , α_{24} and α_{25} .	72
Chapter	5.		ical derivation of the OAC or a continuous stirred tank	77
	5.1.	Optimal a	adaptive control (OAC) system	77
	5.2.	Optimal 1	P of OAC scheme	81
	5.3.	Determina 8 12.	ation of Optimal P coefficient	83
	5.4.	Optimal 1	P + I of OAC scheme	86
•	5.5.		ation of Optimal P + I ents, \$21 and \$26.	90
	5.6.	Optimal 1	P + I + D of OAC scheme	96
	5.7.		ation of Optimal P + I + D ents, β_{21} , β_{26} and β_{27} .	98
Chapter	6.		e of the general schemes of r a continuous stirred tank	106
	6.1.	General S	Scheme 1.	106
	6.2.	General S	Scheme 2.	108
	6.3.	General S	Scheme 3.	110
Chapter	7.	Complete using the	simulation on OMRAC for a CSTR e TR-10 and TR-48 analogue and	112

Page

		9	Pag e
Chapter	7 (con	tinued)	**
	7.1.	General case consideration for a partially simulated CSTR	112
	7.2.	Magnitude scaling and time scaling	116
	7.3.	Modified linearisation coefficients	119
	7.4.	Programming the computer	121
	7.5.	Potentiometer and amplifier assignments	128
	7.6.	Operation of the complete simulation	142
	7•7•	Discussion and analysis of the theoretical results from the complete simulation	144
PART II	. <u>ON</u>	-LINE COMPUTER CONTROL WORK	
Chapter	8.	On-line computer OMRAC system	199
	8.1.	Modified experimental apparatus	199
	8.2.	Interface system design	205
ä	8.3.	Programming the computer	211
Chapter	9.	Commissioning of on-line computer operation	220
	9.1.	Test run	220
	9.2.	Two computers joined for on-line operation	221
\$	9.3.	Smooth plot of fluctuating reactor temperature	223
	9.4.	Effect of initial temperature setting for partially simulated CSTR	223
	9.5.	Determination of $\left[\begin{array}{c} F_{\text{cs}} \\ F_{\text{cm}} \end{array}\right]_{\text{final}}$	226
	9.6.	Effect of feed flowrate step change on partially simulated CSTR	227
Chapter	10.	Operation and analysis of on-line computer OMRAC	235
	10.1.	On-line computer OMRAC operation	235
	10.2.	Comparison of type 1 and type 2 on-line operation	240

			Page
Chapter	10 (co	ntinued)	
	10.3.	Comparison and analysis of process dynamics response and phase-plane trajectories	240
	10.4.	Comparison and analysis of Optimal control law	242
	10.5.	Comparison and analysis of Optimal PID control	243
	10.6.	Comparison and analysis of OMRAC stability	246
	10.7.	Q and (-AH) calculations from experimental data	247
Chapter	11.	Optimal adaptivity	328
	11.1.	Definition	328
	11.2.	Optimal adaptivity of complete simulation	329
	11.3.	Optimal adaptivity of on-line operation	329
Chapter	12.	Conclusions .	347
	12.1.	Overall conclusions for OMRAC system	347
	12.2.	Overall conclusion for on-line computer control system design and operation	349
	12.3.	Suggestions for future work	353
Appendio	es (wit	th index)	354

Nomenclature

Bibliography

INDEX TO TABLES

Table No.	Title	Page
2.1.	A general summary of the current literature on the adaptive control system	34
2.2.	A general summary of the current literature of model reference adaptive control system	37
3.1.	A brief comparison between OMRAC and MRAC	44
7.1.	Magnitude scaling	116
7.2.	Potentiometer assignment sheet for the OMR scheme (Fig. 7.1.)	133
7.3.	Amplifier assignment sheet for the OMR scheme (Fig. 7.1.)	135
7.4.	Potentiometer setting assignment sheet for the OAC scheme (Fig. 7.2.)	137
7.5.	Potentiometer setting assignment sheet for the OAC scheme (Figs. 7.3, 7.4, 7.5 and 7.6)	138
7.6.	Amplifier assignment sheet for the OAC scheme (Fig. 7.2)	139
7.7.	Amplifier assignment sheet for the OAC scheme (Figs. 7.3, 7.4, 7.5 and 7.6)	141
7.8.	Computer OMRAC operation for complete simulation	145
10.1.	On-line computer OMRAC operation	236
10.2.	Q and (-4H) values calculated from on-line experimental data for cases 1.1 and 1.2.	250
10.3.	Q and (-AH) values calculated from on-line experimental data from cases 1.3 and 1.4.	251
10.4.	Q_g and (-AH) values calculated from on-line experimental data from cases 2.1, 2.2, and 2.3.	252
10.5.	Q and (-AH) values calculated from on-line experimental data for cases 3.1, 3.2 and 3.3.	253

Table No.	Title	Page
10.6.	Q and (-AH) values calculated from on-line experimental data for cases 4.1.and 4.2.	254
10.7.	Q_g and (- Δ H) values calculated from on-line experimental data for cases 5.1, 5.2 and 5.3.	255
10.8.	Q_g and (-AH) values calculated from on-line experimental data for cases 6.1, 6.3 and 6.5.	256
10.9.	Q_g and $(-\Delta H)$ values calculated from on-line experimental data for cases 7.1, 7.2 and 7.3.	257
10.10.	Q and (-AH) values calculated from on-line experimental data for cases 8.1 and 9.1.	258
10.11.	Q and (-AH) values calculated from on-line experimental data for cases 10.1, 10.2 and 10.3.	259

.

INDEX TO FIGURES

and the second s		
Figure No.	Title	Page
1.1.	Block diagram of overall research work in OMRAC of a CSTR using on-line hybrid	4.1
	computer	10 m
2.1.	Adaptive contrik system: usual definition	8.1
2.2.	Adaptive control system: modified definition	8.1.
2.3.	General type of model reference adaptive control system	11.1
2.4.	General type of identification adaptive control system	11.1
2.5.	The effect of sinusoidal perturbation, upon a performance index function	23.1.
2.6.	Liapunov method for model reference adaptive control	23.1
2.7.	Optimal adaptive control by identification	29.1
3.1.	General scheme of optimal model reference adaptive control	43.1
3.2.	Optimal phase-plane trajectory	48.1.
3.3.	Changed and unpredicted optimal phase-plane trajectory	48.1
3.4.	Optimal state variable profile as OMR scheme	48.2
3.5.	Optimal phase-plane trajectory as OMR scheme	48.2
6.1.	Structure of general Scheme I of OMRAC	107
6.2.	Structure of general scheme II of OMRAC	109
6.3.	Structure of general scheme III of OMRAC	111
7.1.	Computer diagram of OMR scheme	129
7.2.	Computer diagram of OAC scheme	130
7.3.	Computer diagram of optimal PID control law generation	131
7.4	Computer diagram of OMR optimal control law generation	131

Figure No.	Title	Page
7.5.	Computer diagram of performance response	132
7.6.	Computer diagram of optimal control law constraints	132
7.7.	OMRAC of complete simulation, C vs t, Case 1.1: F decrease 10%, optimal P	151
7.8.	OMRAC of complete simulation, C vs T Case 1.1: F decrease 10%, optimal P	152
7.9.	OMRAC of complete simulation, U* vs.t. Case 1.1 : F decrease 10%, optimal P	153
7.10.	OMRAC of complete simulation, C vs t. Case 1.2: F decrease 20%, optimal P	154
7.11.	OMRAC of complete simulation, U* vs t. Case 1.2: F decrease 20%, optimal P	155
7.12.	OMRAC of complete simulation, C vs t. Case 1.3: F decrease 30%, optimal P	156
7.13.	OMRAC of complete simulation, U* vs t. Case 1.3: F decrease 30% optimal P	157
7.14.	OMRAC of complete simulation, C vs to Case 1.4: F decrease 40%, optimal P	158
7.15.	OMRAC of complete simulation, U* vs t. Case 1.4: F decrease 40%, optimal P	159
7.16.	OMRAC of complete simulation, C vs t. Case 2.1: F increase 10%, optimal P	160
7.17.	OMRAC of complete simulation, C vs T. Case 2.1: F increase 10%, optimal P	161
7.18.	OMRAC of complete simulation, U* vs t. Case 2.1: F increase 10%, optimal P	162
7.19.	OMRAC of complete simulation, C vs t. Case 2.2: F increase 20%, optimal P	163
7.20.	OMRAC of complete simulation, U* vs t. Case 2.3: F increase 20%, optimal P	164
7.21.	OMRAC of complete simulation, C vs t. Case 3.1: a exponential decay 20%, optimal P	165

Figure No.	Title	Page
7.22.	OMRAC of complete simulation, C vs t. Case 3.2: a exponential decay 30%, optimal P	166
7.23.	OMRAC of complete simulation, U* vs t. Case 3.2: a exponential decay 30%, optimal P	167
7.24.	OMRAC of complete simulation, C vs t. Case 3.3: a exponential decay 40%, optimal P	168
7.25.	OMRAC of complete simulation, C vs T. Case 3.3: a exponential decay 40%, optimal P	169
7.26.	OMRAC of complete simulation, C vs t. Case 4.1; combined parameters change: F increase 10%, a exponential decay 20%, optimal P	170
7.27.	OMRAC of complete simulation, C vs T. Case 4.1: combined parameters change: F increase 10%, a exponential decay 20%, optimal P	171
7.28.	OMRAC of complete simulation, U* vs t. Case 4.1: combined parameters change: F increase 10%, a exponential decay 20%, optimal P	172
7.29.	OMRAC of complete simulation, C vs t. Case 5.1: combined parameters change; optimal P + I	173
7.30.	OMRAC of complete simulation, U* vs t. Case 5.1 : combined parameters change; optimal P + I	174
7.31.	OMRAC of complete simulation, C vs t. Case 5.2: combined parameters change; optimal P + I	175
7.32.	OMRAC of complete simulation, C vs T. Case 5.2: combined parameters change; optimal P + I	176
7.33.	OMRAC of complete simulation, U* vs t. Case 5.2 : combined parameter change; optimal P + I	177
7.34.	OMRAC of complete simulation, C vs t. Case 6.1: combined parameter change; optimal P + I + D	178

Figure No.	Title	Page
7.35.	OMRAC of complete simulation, C vs t. Case 6.2: combined parameters change; optimal P + I + D	179
7.36.	OMRAC of complete simulation, C vs T. Case 6.2: combined parameters change; optimal P + I + D	180
7.37.	OMRAC of complete simulation, U* vs t. Case 6.2: combined parameters change; optimal P + I + D	181
7.38.	OMRAC of complete simulation, C vs t. Case 7.1: combined parameters change; different initial conditions, optimal P, (2nd quadrant)	182
7.39.	OMRAC of complete simulation, C vs T Case 7.1: combined parameters change; different initial conditions, optimal P (2nd quadrant)	183
7.40.	OMRAC of complete simulation, U*vs t Case 7.1: combined parameters change; different initial conditions, optimal P (2nd quadrant)	184
7.41.	OMRAC of complete simulation, C vs t. Case 7.2: combined parameters change; different initial conditions, optimal P (3rd quadrant)	185
7.42.	OMRAC of complete simulation, C vs T. Case 7.2: combined parameters change; different initial conditions, optimal P (3rd quadrant)	186
7.43.	OMRAC of complete simulation, C vs t. Case 7.3: combined parameters change; different initial conditions, optimal P, (4th quadrant)	187
7.44.	OMRAC of complete simulation, C vs T. Case 7.3: combined parameters change; different initial conditions, optimal P, (4th quadrant)	188
7.45.	OMRAC of complete simulation, U vs t. Case 7.3: combined parameters change; different initial conditions, optimal P, (4th quadrant)	189

Figure No.	Title	Page
7.46.	OMRAC of complete simulation, C vs t. Case 8.1: combined parameters change: different OMR, optimal P.	190
7.47.	OMRAC of complete simulation, C vs T. Case 8.1: combined parameters change; different OMR, optimal P	191
7.48.	OMRAC of complete simulation, C vs t. Case 9.1 : combined parameters change: different set-point, optimal P	192
7.49.	OMRAC of complete simulation, C vs T. Case 9.1: combined parameters change; different set-point, optimal P.	193
7.50.	OMRAC of complete simulation, U* vs T. Case 9.1: combined parameters change; different set-point, optimal P	194
7.51.	OMRAC of complete simulation, C vs t. Case 10.1; combined parameters change; different C as a load variable, Optimal P	195
7.52.	OMRAC of complete simulation, C vs T. Case 10.1: combined parameters change; different C as a load variable, Optimal P.	196
7.53.	OMRAC of complete simulation, C vs t. Case 10.2: combined parameters change; different C as a parameter, optimal P	197
7.54.	OMRAC of complete simulation, C vs T. Case 10.2: combined parameters change; different C as a parameter, optimal P	198
8.1.	Functional diagram of on-line computer OMRAC system	200
8.2.	Modified experimental apparatus for on-line computer OMRAC system	201
8.3.	Change of switch and fuse location on field controlled servomotor	203
8.4.	Functional diagram of F interface system design	207
8.5.	Functional diagram of Q_g interface system design	210

Figure No.	Title	Page
8.6.	Computer diagram of on-line computer OAC scheme	217
8.7.	Computer diagram of Q interface system	218
8.8.	Computer diagram of Q interface system	219
9.1.	Smooth plot of fluctuating reactor temperature by using a filter technique	229
9.2.	Development of initial temperature setting for on-line operation, T vs t (unadapted operation)	230
9.3.	Development of initial temperature setting for on-line operation, C vs t (unadapted operation)	231
9.4.	Development of initial temperature setting for on-line operation, C vs t (optimal control operation)	232
9.5.	Reliability and reproducibility of on-line unadapted operation, C vs t.	233
9.6.	Reliability and reproducibility of on-line optimal control operation, C vs t.	234
10.1.	OMRAC of on-line operation, C vs t. Case 1.1 (Type 1): F decrease 10%, optimal P	260
10.2.	OMRAC of on-line operation, C vs T. Case 1.1 (Type 1): F decrease 10%, optimal P	261
10.3.	OMRAC of on-line operation, F vs t. Case 1.1 (Type 1): F decrease 10%, optimal P	262
10.4.	OMRAC of on-line operation, C vs t. Case 1.2 (Type 1): F decrease 20%, optimal P	263
10.5.	OMRAC of online operation, F vs t. Case 1.2 (Type 1): F decrease 20%) optimal P	264
10.6.	OMRAC of on-line operation, C vs t. Case 1.3: F decrease 10%, optimal P	265
10.7.	OMRAC of on-line operation, C vs T. Case 1.3: F decrease 10%, optimal P	266

Figure No.	Title	Page
10.8.	OMRAC of on-line operation, F _c vs t. Case 1.3: F decrease 10%, optimal P	267
10.9.	OMRAC of on-line operation, C vs t. Case 1.4: F decrease 20%, optimal P	268
10.10.	OMRAC of on-line operation, F vs t. Case 1.4: F decrease 20%, optimal P	269
10.11.	OMRAC of on-line operation, C vs t. Case 2.1 : F increase 10%, optimal P	270
10.12.	OMRAC of on-line operation, C vs T. Case 2.1: F increase 10%, optimal P.	271
10.13.	OMRAC of on-line operation, F _c vs t. Case 2.1 : F increase 10%, optimal P	272
10.14.	OMRAC of on-line operation, C vs t. Case 2.2: F increase 20%, optimal P	273
10.15.	OMRAC of on-line operation, F vs t. Case 2.2: F increase 20% optimal P	274
10.16.	OMRAC of on-line operation, C vs t. Case 2.3 (Type 1): F increase 20%, optimal P	275
10.17.	OMRAC of on-line operation, F vs t.	
6 4	Case 2.3 (Type 1): F increase 20%, optimal P	276
10.18.	OMRAC of on-line operation, C vs t. Case 3.1: a exponential decay 20% optimal P	277
10.19.	OMRAC of on-line operation, F _c vs t. Case 3.1: a exponential decay 20%, optimal P	278
10.20.	OMRAC of on-line operation, C vs t. Case 3.2: a exponential decay 30%, optimal P	279
10.21.	OMRAC of on-line operation F vs t.	
	Case 3.2: a exponential decay 30%, optimal P	280
10.22.	OMRAC of on-line operation, C vs t. Case 3.3: a exponential decay 40%, optimal P	281

Figure No:	Title	Page
10.23.	OMRAC of on-line operation C vs T. Case 3.3: a exponential decay 40%, optimal P	282
10.24.	OMRAC of on-line operation, F _c vs t. Case 3.3: a exponential decay 40%, optimal P	283
10.25.	OMRAC of on-line operation, C vs t. Case 3.4: a exponential decay 40%, optimal P (for high weighting factors)	284
10.26.	OMRAC of on-line operation, F _c vs t. Case 3.4: a exponential decay 40%, optimal P (for high weighting factors)	285
10.27.	OMRAC of on-line operation, C vs t. Case 4.1 (type 1): combined parameters change: F decrease 10%, a exponential decay 20%, optimal P	286
10.28.	OMRAC of on-line operation, F _c vs t. Case 4.1 (Type 1): combined parameters change: F increase 10%, a exponential decay 20%, optimal P	287
10.29.	OMRAC of on-line operation, C vs t. Case 4.2: combined parameters change: F increase 10%, a exponential decay 20%, optimal P	288
10.30.	OMRAC of on-line operation C vs T. Case 4.2: combined parameters change: F increase 10%, a exponential decay 20%, optimal P	289
10.31.	OMRAC of on-line operation, F vs T. Case 4.2: combined parameters change: F increase 10%, a exponential decay 20% optimal P	290
10.32.	OMRAC of on-line operation C vs t. Case 5.1 : combined parameters change; optimal P + I	291
10.33.	OMRAC of on-line operation F_c vs t. Case 5.1 : combined parameters change; optimal $P+I$	292

Figure No.	Title	Pago
10.34.	OMRAC of on-line operation, C vs t. Case 5.2: combined parameters change; optimal P + I	293
10.35.	OMRAC of on-line operation, C vs T. Case 5.2: combined parameter change; optimal P + I	294
10.36.	OMRAC of on-line operation, F _c vs t. Case 5.2 : combined parameters change; optimal P + I	295
10.37.	OMRAC of on-line operation, C vs t. Case 5.3: combined parameters change; optimal P + I	296
10.38.	OMRAC of on-line operation, C vs T. Case 5.3: combined parameters change; optimal P + I	297
10.39.	OMRAC of on-line operation, C vs t. Case 6.1: combined parameters change; optimal P + I + D	298
10.40.	OMRAC of on-line operation C vs T. Case 6.1 : combined parameters change; optimal P + I + D	299
10.41.	OMRAC of on-line operation, C vs t. Case 6.2: combined parameters change: optimal P + I + D	300
10.42.	OMRAC of on-line operation, C vs T. Case 6.2: combined parameters change; optimal P + I + D	301
10.43.	OMRAC of on-line operation, C vs t. Case 6.3: combined parameters change; optimal P + I + D	302
10.44.	OMRAC of on-line operation, F _c vs t. Case 6.3: combined parameters change; optimal P + I + D	303
10.45.	OMRAC of on-line operation C vs T. Case 6.3: combined parameters change; optimal P + I + D	304
10.46.	OMRAC of on-line operation, C vs t. Case 6.4: combined parameters change; optimal P + I + D	305

Figure No.	Title	Page
10.47.	OMRAC of on-line operation, C vs T. Case 6.4: combined parameters change; optimal P + I + D	306
10.48.	OMRAC of on-line operation, C vs t. Case 6.5: combined parameters change; optimal P + I + D	307
10.49.	OMRAC of on-line operation, C vs T. Case 6.5: combined parameters change; optimal P + I + D	308
10.50.	OMRAC of on-line operation, C vs t. Case 7.1: combined parameters change; different initial conditions, optimal P.	309
10.51.	OMRAC of on-line operation, C vs T. Case 7.1: combined parameters change; different initial conditions, Optimal P	310
10.52.	OMRAC of on-line operation, F _c vs t. Case 7.1: combined parameters change; different initial conditions, optimal P	311
10.53.	OMRAC of on-line operation, C vs t. Case 7.2: combined parameters change; different initial conditions, optimal P	312
10.54.	OMRAC of on-line operation, C vs T. Case 7.2: combined parameters change; different initial conditions, optimal P	313
10.55.	OMRAC of on-line operation F_c vs t. Case 7.2: combined parameters change; different initial conditions, optimal P	314
10.56.	OMRAC of on-line operation, C vs t. Case 7.3: combined parameters change; different initial conditions, optimal P	315
10.57.	OMRAC of on-line operation, C vs T. Case 7.3: combined parameters change; different initial conditions, optimal P	316
10.58.	OMRAC of on-line operation, F _c vs t. Case 7.3: combined parameters change; different initial conditions, optimal P	317
10.59.	OMRAC of on-line operation, C vs t. Case 8.1: combined parameters change; different OMR, optimal P	318

Figure No.	Title	Page
10.60.	OMRAC of on-line operation, C vs T. Case 8.1: combined parameters change; different OMR, optimal P	319
10.61.	OMRAC of on-line operation, C vs t. Case 9.1 : combined parameters change; different set-point, optimal P	320
10.62.	OMRAC of on-line operation, C vs T. Case 9.1: combined parameters change; different set-point, optimal P	321
10.63.	OMRAC of on-line operation, C vs t. Case 10.1: combined parameters change; different C as load variable, optimal P	322
10.64.	OMRAC of on-line operation, C vs T. Case 10.1: combined parameters change; different C as load variable, optimal P.	323
10.65.	OMRAC of on-line operation, C vs t. Case 10.2.: combined parameters change; different C as load variable, optimal P	324
10.66.	OMRAC of on-line operation, C vs T. Case 10.2: combined parameters change; different C as load variable, optimal P	325
10.67.	OMRAC of on-line operation, C vs t. Case 10.3: combined parameters change; different C as parameter, optimal P	326
10.68.	OMRAC of on-line operation C vs T. Case 10.3: combined parameters change; different C as parameter, optimal P	327
11.1.	Optimal adaptivity, ψ , of complete simulation for feed flowrate change and optimal P	331.
11.2.	Optimal adaptivity, ψ , of complete simulation for catalyst activity and combined parameters change and optimal P	332
11.3.	Optimal adaptivity, ψ , of complete simulation for combined parameters change and optimal P + I	333
11.4.	Optimal adaptivity, ψ , of complete simulation for combined parameters change and optimal P + I + D	334

Figure No.	Title	Page
11.5.	Optimal adaptivity, ψ , of complete simulation for combined parameters change and optimal P and different initial conditions	335
11.6.	Optimal adaptivity, ψ , of complete simulation for combined parameter change and optimal P and different OMR	336
11.7.	Optimal adaptivity, ψ , of complete simulation for combined parameters change and optimal P and different set-point	337
11.8.	Optimal adaptivity, ψ , of complete simulation for combined parameters change and optimal P and didderent inlet concentration change	338
11.9.	Optimal adaptivity, ψ , of on-line operation for feed flowrate change and optimal P	339
11.10.	Optimal adaptivity, ψ , of on-line operation for catalyst activity and combined parameter change and optimal P	340
11.11.	Optimal adaptivity, ψ , of on-line operation for combined parameters change and optimal P + I	341
11.12.	Optimal adaptivity, ψ , of on-line operation for combined parameters change and optimal P + I + D	342
11.13.	Optimal adaptivity, ψ , of on-line operation for combined parameters change and optimal P and different initial conditions	343
11.14.	Optimal adaptivity, ψ , of on-line operation for combined parameters change and optimal P and different OMR.	344
11.15.	Optimal adaptivity, ψ , of on-line operation for combined parameters change and optimal P and different set-point	345
11.16.	Optimal adaptivity, ψ , of on-line operation for combined parameters change and optimal P and different inlet concentration change	346

CHAPTER 1. INTRODUCTION

On the existing equipment for a continuous stirred tank reactor (CSTR), the heat release of an exothermic reaction is partially simulated in the reactor by means of immersion heaters. A study of such a "Partial Simulation Technique" has been made by Buxton at the end of 1970 (80). As an extension of this research work, the following three points have been considered:

- 1. All of the original parameters of the system were assumed to be constant, i.e. it was not adaptive.
- 2. The original control system was designed to incorporate continuous three mode feedback control, i.e. it was not optimal control.
- 3. For the original complete and partial simulation a conventional temperature controller was used, i.e. it was not on-line computer control.

By including a combination of developments to overcome the above three limitations, a single complete system was proposed for the present research work, and strong support is given as a result of a comprehensive literature survey.

The major objectives of this research work were:

- 1. Theoretical development of the optimal model reference adaptive control (OMRAC) system combined with the more complicated general optimal PID control laws.
- Complete simulation of the developed OMRAC system applied to a CSTR using the combined TR-10 and TR-48 hybrid computers.
- On-line computer system design and operation of developed
 OMRAC applied to a CSTR using TR-10 and TR-48 hybrid computers.

All this research work can be represented by a complete block diagram shown in Fig.1.1.

From Fig.1.1. this research is divided into two parts:

Part I. Theoretical and complete simulation work

(Chapters 3, 4, 5,6, and 7).

Part II On-line computer control work (Chapters 8, 9, 10 and 11).

A comprehensive literature survey is shown in Chapter 2, and two systematic summary tables and the discussion indicate the features of originality of this research work.

As an extension of the basic concept of my previous work, (see 2.4.2) (67), a general algorithm and theory of OMRAC system was developed theoretically and complicated general optimal PID control laws for the optimal adaptive control (OAC) scheme were derived in detail and are shown in Chapter 3.

From the theoretical development, the OMRAC scheme is combined with the OMR scheme and the OAC scheme.

Based on Pontryagin's maximum principle, the mathematical derivation both of the OMR scheme and the OAC scheme for a CSTR are shown in Chapters 4 and 5 respectively. A total of twenty-eight non-linear algebraic equations to determine all of the coefficients of different optimal PID control laws were solved by digital computer (Appendix 1). The overall three OMRAC schemes are shown in Chapter 6.

From Chapters 3, 4, 5 and 6 a complete simulation of the developed OMRAC system applied to a CSTR using TR-10 and TR-48 hybrid computers is shown in Chapter 7. All hybrid computer programming with all sealed computer variable equations of the

shown in Figs. 7.1 to 7.6 while the corresponding potentiometer and amplifier settings for each figure and the static checks are shown in Tables 7.2 to 7.7. A total of sixty-nine plotted figures for different operating cases with different conditions are shown in Figs. 7.7. to 7.54. and in Appendix 2. Analysis and discussion of all the theoretical results are shown at the end of this chapter.

In Part I, the theoretical development of OMRAC has been positively proved, and the further work of on-line hybrid computer system design and operation in combination with a partially simulated CSTR is studied and shown in Part II.

On-line computer OMRAC system is shown in Chapter 8.

The overall functional diagram and the modified experimental apparatus designed for the on-line computer OMRAC system are shown in Fig. 8.1 and all calibrations of experimental apparatus are shown in Appendix 4.

The requirements of interface system design as for any industrial transmitter is that the terminal relation between the computer side and the process side must be extremely linear. To meet this requirement, the interface system was designed in detail and is shown in Fig. 8.2. All on-line computer programming of the OMRAC scheme with the interface system designs were programmed in detail and are shown in Fig. 8.5.

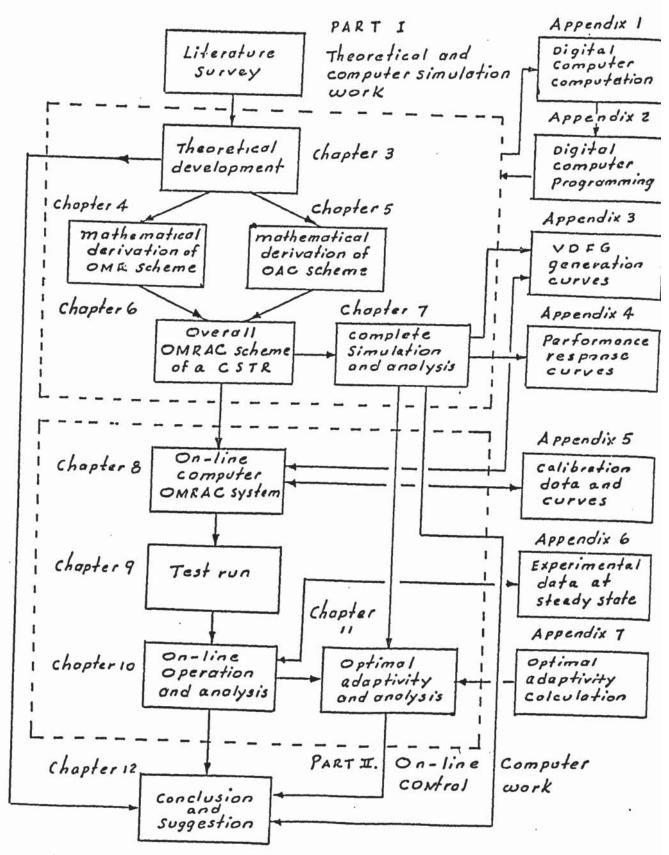
A continuous test run of on-line operation is shown in Chapter 9. The purpose was to test the overall performance of the on-line system and to find successful operating procedures and techniques to produce reliable and reproducible on-line computer OMRAC:

All operation and analysis of on-line computer OMRAC is shown in Chapter 10.

A total of sixty-eight plotted figures for different operating cases with different conditions are shown in Figs. 10.1 to 10.68. Comparison and analysis of process response, phase-plane trajectories, optimal control laws, optimal PID control, OMRAC stability, and experimental data calculations are discussed in detail.

For a quantitative analysis and evaluation of OMRAC both for complete simulation and on-line operation, a new term "Optimal Adaptivity" is introduced in Chapter 11. Overall, sixteen three dimensional figures of optimal adaptivity are shown in Figs. 11.1 to 11.16 and the analysis and discussion follow.

An overall systematic conclusion and suggestion for future OMRAC system work are discussed in detail in Chapter 12.



where: OMR = Optimal model reference

OAC = Optimal adaptive control

OMRAC = Optimal model reference adaptive control

Figure 1.1 Block diagram of overall research work
on OMRAC of a CSTR using an on-line
hybrid computer

CHAPTER 2

LITERATURE SURVEY ON ADAPTIVE CONTROL

For the past decade, adaptive control has been combined with optimal control to give a challenging new area of automatic control research (16,17).

This chapter presents a comprehensive literature survey, brief review, systematic summary and discussion of adaptive control systems. The major sources are based on a series report from William's I/EC Chemical Engineering Fundamental Review of Computers and Process Control between 1958 and 1970⁽¹⁻¹¹⁾, four surveys and reviews^(12,13,14,17), two textbooks^(15,16), several reference books⁽¹⁸⁻²⁴⁾, and forty articles up to the present time^(31~71).

In this chapter, the following six sections are considered:

- 2.1 Basic concept, definition and classification.
- 2.2 General brief review of adaptive control system from known surveys and text-books.
- 2.3 General survey of adaptive control systems from current papers, excluding Chemical Engineering.
- 2.4 General Survey of adaptive control systems in Chemical Engineering.
- 2.5 Summary of the current literature on adaptive control systems:
 - (i) A summary of the current literature on adaptive control systems (Table I).

(ii) A summary of current literature on model reference adaptive control systems (Table II).

2.6 Discussion.

2.1 Basic concept, definition and classifications

Since Draper and Li (18) published the first research paper on adaptive control in 1951 (sometimes called self-optimizing control (17)) the definition and classification of adaptive control systems have not been unified until the present time. In this section definitions are proposed upon which the whole research work will be based, and classification is given for all of the systematic survey, summary and discussion in this chapter.

2.1.1. Basic concept

In chemical processes, frequently the optimal operating conditions will be influenced by some of the uncontrollable and unmeasurable parameters and load variables such as inlet concentration, temperature profile, catalysis activity, flow and mixing pattern, overall heat transfer rate, mass transfer rate and ambient external conditions. If any process operates in the presence of such an unmeasurable, uncontrollable parameter or load variable the optimal operating condition of the process can still adapt by self-adjustment or self-modification; this is the basic concept of adaptation.

Actually adaptation which is the ability of selfadjustment and self-modification in response to changing conditions of environment or structure is a fundamental attribute of living organisms (12).

2.1.2 Definition

Many definitions, varying from the specific to very general, have been advanced for adaptive control by workers such as Mishkin and Braun (15), Eveleigh (13,16), Shinners (14) and Lee, Adams and Gaines (19). Here one general definition from Shinners is introduced as follows:

An adaptive control system is basically a feedback control system which automatically achieves a desired response or performance index in the presence of extreme change in the controlled system's parameters and major external disturbance.

From the above definition, an adaptive control system should contain the following characteristics:

- (1) The system operates under a changing situation.
- (2) The master control loop is always a feedback control system
 - (3) The system has a set of adjustable controller parameters;
 in servomechanisms it is always gain, filter time
 constant, while in process control it is the settings
 Kc. Ti. Td of the PID controller.
- (4) Ability to determine system performance index (PI)

 (index of performance, figure of merit, objective
 function) or desired operating point or response.
- (5) Ability to maintain a good quality of control with respect to certain PI by automatic adjustment of the set of adjustable parameters (Fig. 2.1).

In this research work, the modified definition of adaptive control system which is extended and based on my previous research work (67) will be defined as follows:

Adaptive control is the optimal control of a process in the presence of unmeasurable and uncontrollable parameters and load wariables; the optimal control law can be modified by an adaptive controller in which different types of adaptation can be generated (Fig. 2.2).

Adaptive control defined as above may be called optimal adaptive control, the differences between these two definitions are:

- (i) clear emphasis that the changed process situation arises from unmeasurable and uncontrollable parameters or load variables.
- (ii) Adjustment is achieved directly by optimal control system instead of by a conventional control system.
- (iii) Adjustment is achieved directly by a modified optimal control law instead of by conventional adjustment of the parameters of PID controller.

2.1.3. Classifications:

The authors of three excellent surveys (12-14) suggested their different classifications of adaptive control systems from the different points of view and approaches which are used in analysis and design.

Aseltine, Manici and Sarture (12) suggested the separation of the adaptive system into five classes:

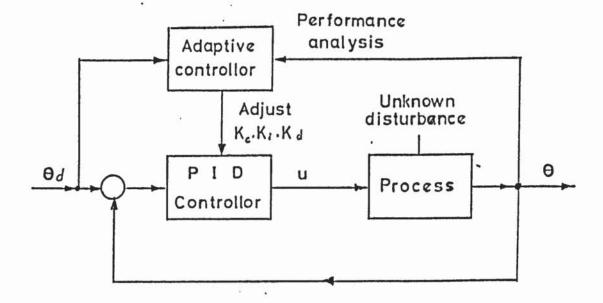


Figure 2.1 Adaptive control system by usual definition

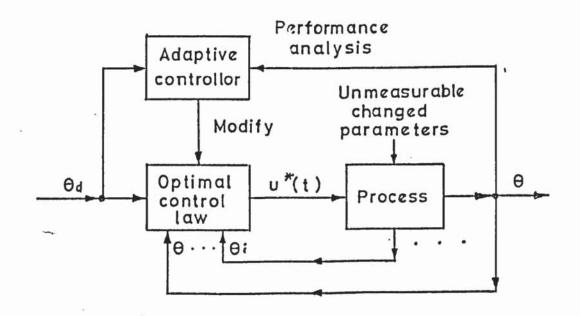


Figure 2.2 Adaptive control system by modified definition

- (1) Passive or environment adaptation;
- (2) Input adaptation;
- (3) Extremum adaptation;
- (4) System variable adaptation;
- (5) System characteristic adaptation.

For the first two classes, the system adaptation is based on different locations of disturbance (environment and input). For the third class, the system adaptation is based on operating optimal performance. For the last two classes the system adaptation is based on different locations of measurement (variables and transfer functions). This classification is thus not unified.

Eveleigh (13) suggested separation of the adaptive system into four classes:

- (1) Input adaptive
- (2) Plant adaptive
- (3) Parameter adaptive
- (4) Signal synthesis adaptive.

For the first two classes, the system adaptation is based on different locations of the disturbance (input and plant). The classifications of (3) and (4) are to distinguish between direct parameter adjustment and signal synthesis adaptive systems.

So this classification is not unified either.

Shinners (14) suggested four classes:

- (1) Model reference adaptive control system
- (2) Non-linear adaptive control system

- (3) Impulsive-response adaptive control system
- (4) Digital computer controlled adaptive control system.

For class (1), the system adaptation is based on a very important type of adaptation. For class (2), the system adaptation is based on the non-linear element of the system. For class (3), the system adaptation is based on one kind of identification method (16). For class (4), the system is adapted by using a digital computer to compute the forcing function required to obtain the desired response by iterative operation.

All of these four classes are based on different approaches and so this is not a unified classification.

According to the basic type and idea of adaptation in most of the past adaptive control research work, it is desirable to suggest a unified classification of adaptive control systems divided into the following three general classes from which all systematic survey, summary and discussion in this chapter will arise:

- (1) 'Model Reference adaptive control
- (2) Identification adaptive control
 - (3) System characteristic and optimization adaptive control
 - (1) Model Reference Adaptive Control: The master control system response is compared to a known model reference assumed to have the desired response characteristics. The observed response error signal is used to adjust one or more parameters in the master

control system by the adaptive controller, thereby forcing its response to approach that of the model (Fig. 2.3).

- (2) Identification Adaptive Control: Using some form of test signal input, the system is to be adapted by identification of characteristics of the unknown changed parameters or system transfer function or some equivalent form of information (Fig. 2.4).
- (3) System characteristic and optimization adaptive control:

 The system is to be adapted by using system characteristics and/or any optimization techniques to automatically adjust the parameters to achieve optimal performance without definite model reference and identification functions (Fig. 2.1).

2.2. General brief review of adaptive control from known survey and text-books.

There are four general surveys and reviews of adaptive control (12,13,14,17). As a matter of interest the first form of adaptive control was referred to as an optimal control system by Draper and Li (18) in 1951, who reported the automatic adjustment of gasoline engine spark timing and fuel mixing to minimise manifold pressure.

2.2.1. Aseltine, Manici and Sarture (12) gave their survey in 1958. A total of 35 research articles, mostly from AIEE, IRE and ASME between 1951 and 1958 and divided into five classes (see Section 1.1.3) has been reviewed and useful

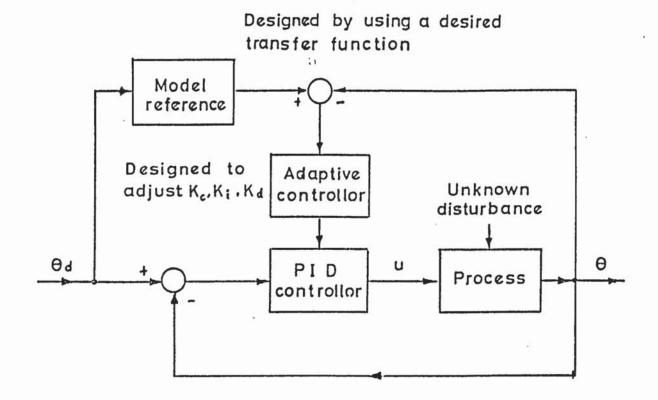


Figure 2.3 General type of model reference adaptive control system

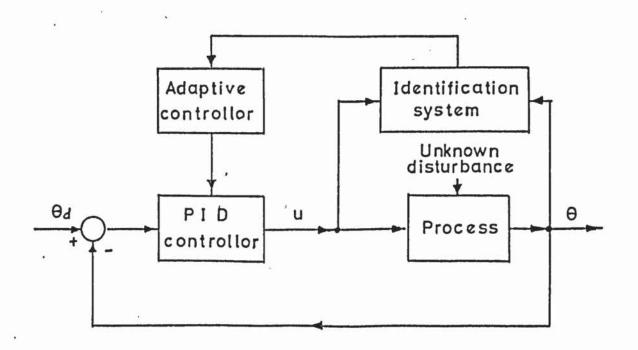


Figure 2. 4 General type of identification adaptive control system

systematic Tables 2.1 and 2.2 for the characteristics of adaptive control systems have been prepared.

- 2.2.2 Oldenburger (17) gave a comprehensive survey both for optimal control and self-optimizing control (adaptive control).

 Over three hundred published articles and books, mostly from AIEE, IRE, AEEE, ASME and Automation and Remote Control, exist but no brief review and systematic summary or analysis of adaptive control from this survey was possible.
- 2.2.3. Shinners (14) also gave a brief review both for optimal control and adaptive control. The author introduced the basic concept of adaptivity, the types of adaptive control (See Section 1.1.3) and several examples of each type were illustrated.

It must be pointed out that the model reference adaptive control system shown in Fig. 2.3, was first designed by M.I.T. Instrumentation Laboratory for use as an adaptive pilot (25). The model is based upon pilot preference, airframe limitations, performance, objective, etc. The gains in the yaw orientation loop, the roll stabilisation loop and the roll-damping loop are automatically adjusted by adaptive control.

2.2.4. Eveleigh (13) gave a more complete general review of adaptive control and most material in this review has been written in his later published book (16). This is only one of the recently published books on adaptive control systems.

The author emphasised both in his review and in his book

that the adaptive control may be broken down into three major functions:

- (i) Identification,
- (ii) decision, and
- (iii) modification.

Identification is defined as the process by which the system is characterised or by which the PI value is measured.

In the decision process, the PI measurements are used to decide how system performance is related to the desired optimum.

Modification is the process of changing the system parameters toward the optimal setting.

Decision and modification are the required basic functions to develop an adaptive controller shown on all five previous figures (Fig. 2.1 \sim Fig.2.5) respectively.

The definition of identification shown above is different from that shown in Chapter 7 of the present author!s book.

Identification shown in Chapter 7 is defined "exclusively as the process of measuring a system transfer function or some equivalent form of information". It is almost the same as the proposed type 2 classification (see Section 2.1.3.).

Actually identification as shown above will be divided into two parts:

(1) Identification of the system which will belong to type 2 classification.

(2) Identification of PI values which will belong to

Type 3 classification.

However, "model reference", the most basic function of adaptive control, was still not included in the author's three major functions.

From the above discussion, the suggested new classification of the three basic types of adaptive control seems reasonable for the representation of all systems.

2.2.5. Several useful techniques in adaptive control

Based upon Eveleigh's book and other reference books, Several useful techniques used in adaptive control will be discussed.

A. Identification problem

Although a variety of identification methods are discussed, the three chosen for emphasis are

- (1) cross-correlation, (2) pulse transfer function method and (3) quasi-linearisation.
- (1) Identification using cross-correlation provides direct information about the system. The output of the cross-correlation results in a point on the impulse response for the system. Additional points on the impulse response may be obtained by introducting additional cross-correlation channels having appropriate delays. This method is limited to linear systems.
- (2) The pulse transfer function method is most appropriate in digital systems.

(3) Quasi-linearisation, a form of gradient method, is similar to the second variation procedure for solving boundary value problems. The basic concept is small signal linearization of the system response about a nominal path through state space. This method is an effective identification procedure which applies to both linear and non-linear systems

Sage (23) in his text-book discussed both continuous and discrete system identification and modeling using quasi-linearisation.

My previous research work (67) developed an identification function by using Z-transform and least square techniques to identify the time varying gain of a second order process.

B. Steepest descent (or ascent) approach to adaptive control

The steepest descent (or ascent) technique has been

The steepest descent (or ascent) technique has been used for static optimization in different fields (26,27).

The strategy for a steepest descent adaptive system is identical to that used for static optimization (28).

Thus assume a PI response surface in n-dimensional parameter space with a well-defined minimum as the optimum point. Let the starting point in parameter space be

$$P_0 = (a_1, a_2, ---a_n)$$

The operating procedure is as follows:

(1) Measure the value of $(\Im(PI)/\Im a_n)$ by perturbation of the a_n falue and observation of the results. Store the results.

(2) Form the vector:

Slope of path
$$P_{0} \longrightarrow P_{1}$$

$$Z = \sum_{l=1}^{n} I_{l} \underbrace{\delta(PI)}{\partial a_{l}}$$

where I_i = standard unit vector in n space and Ξ = slope of path $P_o \rightarrow P_1$

(3) Adjust the system's location by moving to the new parameter position:

$$P_1 = P_0 + k Z$$

where k = adaptive gain

(4) Repeat the process until the optimum value of PI is reached.

PI response surface representative of adaptive control has been emphasised by Eveleigh in his review.

My previous published paper (30) has also discussed the PI response surface generated by steepest descent and approached by using an analogue computer.

C. Sinusoidal-perturbation approach to adaptive control
Figure 2.5 shows a representative variation of PI
with adjustable parameter m, the effect of
sinusoidal-perturbation for offset in both
directions from the optimum is also illustrated.

Let:

$$m(t) = m_1 + c_1 \sin \omega t \qquad (1-1)$$

the first order Taylor's series approximation for PI, J(m,t) is given by

$$J(m_1,t) = J(m_1)t + J'(m_1)c_1 \sin t + J''(m)(c_1 \sin wt)^2$$
 (1-2)

where $J'(m_1) = (\frac{\partial J}{\partial m})$ m = m₁, the slope of the PI curve.

The fundamental frequency component of $J(m_1,t)$ is proportional in magnitude to the slope of J at $m=m_1$, and it changes sign (shifts phase 180°) at $m=m^*$. Thus both the magnitude and sign of (3J/3m) at $m=m_1$ are contained in the w_1 component of $J(m_1,t)$, and an adaptive loop error signal can be derived from the output using a standard (correlation) detector.

Draper and Li⁽¹⁸⁾ first used this technique, Eveleigh discussed the general stability analysis of such techniques⁽²⁹⁾, while Box⁽⁶¹⁾, Alpeter⁽⁶⁹⁾ and Price⁽⁷⁰⁾ all used such techniques on chemical reactors and will be discussed later.

The first book of adaptive control written by

Mishkin and Braun was published in 1961, and gives the
general principles and knowledge for adaptive control.

There are a few optimal control text books (19-22, 24)

containing some knowledge and techniques of adaptive

control which are valuable for reference.

2.3. General survey of adaptive control system from current systems excluding the Chemical Engineering field.

All the material selected in this section was contained in twenty nine articles (1963-1972) and is connection on the survey of model reference. This survey may be linked with the

several earlier surveys discussed in Section 1.2, to give a more complete survey of adaptive control systems.

According to the suggested classification discussed in Section 2.1.3, there are three classes:

- Class 1: Model reference adaptive control system,
- Class 2: Identification adaptive control system.
- Class 3: System characteristic and optimization adaptive control system.
- 2.3.1. Model Reference Adaptive Control System (Class I)

 Model reference system has proved to be one of the most popular and reliable methods in the growing field of adaptive control. The general definition and functional figure has been discussed and shown in Section 2.1.3. A total of twenty articles have been reviewed.

Halbert (31) used the hybrid computer to simulate an aircraft adaptive control system. The proposed adaptive technique utilises predicted as well as measured past information on aircraft behaviour to calculate optimum controller parameters. The optimal performance is determined by a systematic search procedure in parameter space. The search programme is under the direction of the logic elements and employs an analog computer model of the aircraft system solved at high speed for prediction purposes. Kwai (32) presented a technique for controlling two parameters with a known range of variation to give the desired dynamic performance of the system. Desired damping is used as

Model I, and desired natural frequency is used as Model 2.

The equalised maximum overshoot (or under shoot) criterion and the equalised response areas criterion are employed.

A second order system is considered in detail. A simulation study is made on a general purpose digital computer.

White (33) proposed a simple criterion which permits variation in the optimum adaptive parameters to be calculated as the input-signal varies. The approximate equations for the adapting system are formed by using a parameter perturbation technique. The equations are then used to give an estimate of the stability of the adaptive loop. The whole of the theoretical work is supported by extensive analoguesimulation studies.

Dressler (34) proposed a simple adaptation technique derived analytically. By solving the differential equations of the reference model and the adaptive control system, an expression was obtained showing the explicit functional dependence of the performance error on the adaptive parameter.

Graupe and Cassir (35) described a model reference adaptive control system where extrapolation techniques are used for identification and for error-prediction at discrete time intervals. The system employs rectangular adaption pulses of finite duration to minimise a cost-function of predicted square errors.

Pearson and Noonan (36) proposed a modified gradient procedure for the discrete adjustment of parameter in a

model reference adaptive control problem.

Wilkie and Perkins (37) proposed the transformed state variables to pursue dynamically similar models. The parameter vector is adjusted to minimise the effect of the variable plant parameters on the system response.

Bristal, Inaloglu and Steadman (38) proposed a response pattern or shape as the model reference instead of a particular desired response for adaptive control.

Powell (39) employs an adaptive model to estimate the state, dynamic and future trajectories of an unknown plant. By using a speeded-up model, control is automatically synthesised to minimise a performance index.

Price (40) proposed an accelerated gradient method which is capable of adapting rapidly to plant parameter variations. It is based upon the objective of improving the stability characteristics of a gradient type model reference adaptive control system. A design procedure is developed for an nth order linear plant. It is applied to the control of pitch motion for an airframe; simulation results comparing the technique with conventional gradient methods are presented.

Buxton and Powell (41) described the results of a simulated study carried out to demonstrate the feasibility of a self-adaptive automatic carrier landing system. The mean square error index was used as PI, and a suitable gradient algorithm was used as the adaptive control block.

Monopoli (42) proposed a reduction of order technique which is useful in controller design for single input, single

output, linear plants which have transfer functions with zeros and parameters which vary slowly compared with the response time of the plant.

Park (43) and Monopoli (44) proposed the Liapunov direct method (i.e. the second method) to design a model reference adaptive control system and has the advantage over the MIT rule, designed by Osburn, Whitaker and Kezer (45) that the asymptotic stability is a by-product of the design.

From the introduction by Park and Monopoli, this technique was improved and extended by a number of authors, as follows:

Winsor and Roy (46) extended the technique to a broader class of linear, time-invariat plants for n state variables and r control variables.

Landau⁽⁴⁷⁾ extended so that more general results may be obtained in the problem of analysis and synthesis of model reference adaptive control systems from the point of view of stability, using Porov's results in the field of hyperstable systems.

Gromyko and Sankovskii (48) applied the Liapunov direct method to the construction of adaptive systems of the model by combined active (parametric) and passive (signal) adjustments.

Gilbart, Monopoli and Price (49) extended a modified
Liapunov design technique for model reference adaptive control
systems and showed the result in improved system convergence.

Shahein, Ghonaimy and Shen (50) presented two methods for accelerating the convergence in model reference adaptive

control systems. The adaptive loop, incorporating feedback, can be synthesised either directly from a Liapunov function or indirectly from the minimisation of a Liapunov function along the steepest descent path.

The model reference adaptive control system has been well developed using the Liapunov direct method in recent years. Here a simple introduction to the technique is given:

Consider the simple model reference adaptive control a system (Fig. 2.6) where the problem is to find/suitable adaptive loop to adjust K_c so that K_cK_v is eventually equal to the model gain K_v , although it is initially different from K_v . Using a tentative Liapunov function:

$$V = e^2 + \lambda x^2 \quad (\lambda \text{ constant } > 0)$$
 (1-3)

where V = Liapunov function,

e = response error,

$$x = K - K_{c}K_{v},$$

K = controller gain

 $K_v = control value gain$

then
$$\dot{x} = -K_v \dot{K}_c$$
 (1-4)

$$\frac{dV}{dt} = 2e\dot{e} + 2\lambda x\dot{x}$$

$$= 2e \left[-\frac{e}{L} + \frac{x\theta_d(t)}{T} \right] + 2\lambda x\dot{x} \qquad (1-5)$$

where $\Theta_{d}(t) = input$

L = time constant

Now let

$$\dot{x} = -e\theta_{d}(t)/\lambda t \tag{1-6}$$

so that

$$\frac{dV}{dt} = -2e^2/L \le 0 \quad \text{for any value of e} \qquad (1-7)$$

Liapunov's theorem states that a system is stable if a scalar function $V(x_1, x_2, \dots, x_n)$ is found with the following properties:

- 1. Outside the origin, $V(x_1, x_2,x_n) > 0$
- 2. V(0) = 0
- 3. $V(x_1, x_2, ..., x_n)$ is continuous and has continuous first partial derivatives in a region R about the origin

4.
$$\mathring{V} = \frac{\partial V(x_1, x_2, \dots, x_n)}{\partial t} \leqslant 0 \text{ in } R$$

Hence, equation (1-6) is a necessary condition for stability of the adaptive control system.

From equations (1-4) and (1-6):

$$K_{c} = \frac{e\theta_{d}(t)}{\sum K_{v}t}$$
 (1-8)

or
$$K_e = \left[\frac{B'}{s}\right] \left[e \cdot \theta_d(t)\right]$$
 (1-9)

where
$$B' = \frac{1}{\lambda K_y t}$$
 (1-10)

This gives a new system represented by a Liapunov function and shown in Fig. 2.6.

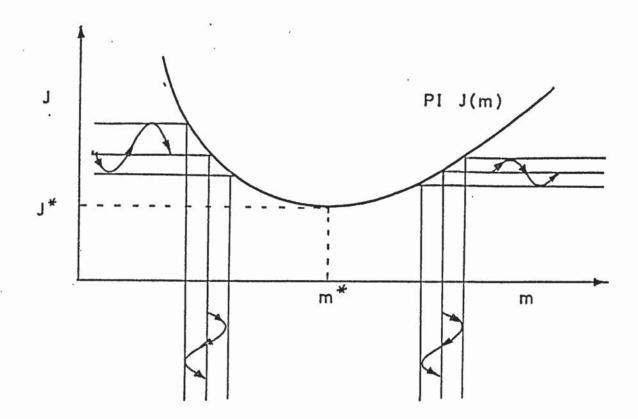


Figure 2.5 The effect of sinusoidal pertubation upon a PI function

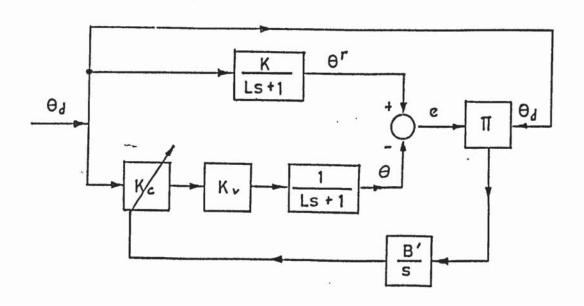


Figure 2.6 Liapunov method for model reference adaptive control

2.3.2. Identification Adaptive Control System (Class 2)

Two approaches to identification are normally used.

System variable identification attempts to minimise some arbitrary error criterion by identification of the system variables. System characteristic identification or plant identification requires the determination of some information about the system such as transfer function, impulse response, damping ratio of a dominant part of the poles, or the magnitude and phase of the system output in response to a test signal.

A total of four articles are reviewed.

Womack and Watt (51) proposed an identification method which is achieved by a high frequency sinusoidal test signal. A linear control system with two variable parameters is considered, and the adaptive system is simulated by analogue computer.

Kershow (52) proposed a plant identification in which the adaptive scheme is based on measured transfer characteristics and includes an impulse transfer function computer to calculate the transfer function of the plant from the transient response to a driving signal.

Puri (53) proposed an identification algorithm based upon discrete orthogonal functions and used it to identify the flight motion parameters. This research deals with a digital autopilot design for flight path control. Three subroutines were contained in the adaptive control computer: identification subroutine, optimal synthesis sub-routine and

adaptive compensation subroutine.

Obradovic (54) proposed an adaptive and optimal time control method for processes with time varying coefficients. The method is primarily based on the area formed between the curves presenting the input and output variables of a controlled process. The method permits the process identification in terms of an equivalent linear transfer function with time delay during a real control transient.

2.3.3. System characteristics and Optimization adaptive control systems (Class 3)

Any adaptive control system without definite model reference and identification functions but using system characteristics and/or optimization techniques to generate an adaptive controller belongs to Class 3.

A total of five articles are reviewed.

Banham and Smith (55) suggest that by a linear representation of the non-linear system a controller can be designed with adaptive features, and provides optimum compensation for transient system requirements. The adaptive feature is used to adjust the controller parameters K_C and T_i required to maintain an optimum combination of closed lopp system response and stability over the designed range of process operation. The method was applied to a forced draft blower.

Aoki (56) proposed the concept relating to loss of performance in certain adaptive control systems. These concepts are useful in determining or in bounding the possible

loss in the adaptive control system where certain parameters are mot known precisely. The connection with the minimax principle of statistical decision theory was also pointed out by him.

Pearson and Sarachik (57) did work related to an approach introduced by Kulikowski (58) for adaptive optimal control of non-linear systems. In this approach, the plant dynamics are represented by an operator which transforms the input time functions into corresponding output time functions.

Pearson (59) in another similar work extended and modified the approach to adaptive optimal control proposed by Kulikowski. Emphasis was placed upon optimizing the steady-state system performance in which the desired output of the plant is a periodic function of time.

Pearson (60) proposed a modified gradient procedure for making discrete-time changes in the adjustable parameter of a continuous-time non-linear system during normal operating conditions. The algorithm employs the best available estimate of the unknown plant parameters as well as an estimate of the disturbance state and the outlet variables.

2.4. General Survey of adaptive control systems applied in Chemical Engineering

A general survey of adaptive control systems applied in the Chemical Engineering field is given in this separate section, and a total of eleven articles (1962-1971) are reviewed.

2.4.1. Model Reference Adaptive Control System (Class 1)

Marcus and Hougen (61) proposed a model reference

adaptive control scheme applied to a simulated heat

exchanger control system. Automatic self-adjustment of

parameters of a PID controller was achieved to maintain the

dynamic performance in the presence of a wide variation of

process parameters; shell-side flow rate and tube-side inlet

temperature were considered.

Crandall and Stevens (62) applied model reference adaptive control to a continuous stirred tank reactor. The performance index was the integral of the square of the derivation of the output composition from a value determined by a reference model. (or response error). The adaptive controller was incorporated with an automatic identification scheme and decision process, and operated in the presence of disturbances in cooling water temperature and/or catalyst activity.

Casciano and Staffin (63) proposed an adaptive control scheme which used desired first order differential equations as model references. The adaptive loop was operative only during a transient and corrected only in the direction of mismatch between process and model. A first order process with varying time constant and two mode controller (P and I) were considered. The effects on system stability with a pure time delay, or an additional pole in the process are presented.

Ryan and Crandall (64) developed a method for applying classical minimisation techniques to forms of algebraic performance indices for use in optimal adaptive control systems. Essentially, the derivative of a general objective function is constrained to be equal to the integrand of a desired integral performance index. Derivatives of the objective function can be taken with respect to the controllable parameters, set equal to zero, and solved for the setting which minimises the performance index over a period of time. The method has been applied to a stirred tank reactor, and a two mode (PI) and three mode (PID) controller were used. The adaptive control system adjusted the controller settings periodically.

Ahlgren and Stevens (65) developed a normalised version of the model reference adaptive control system including suitable procedures for adjusting adaptive control gains and demonstrated excellent adaptive performance for a simulated stirred tank reactor. The three constants in a conventional PID controller were simultaneously adjusted to accomplish this adaptation.

2.4.2. Identification Adaptive Control Systems (Class 2)

Most identification methods require that a small test signal be superimposed on the input signal. The following two identification methods gave different approaches to this.

Mellichamp. Coughanowr and Koppel (66) proposed an identification scheme. The method employed a small

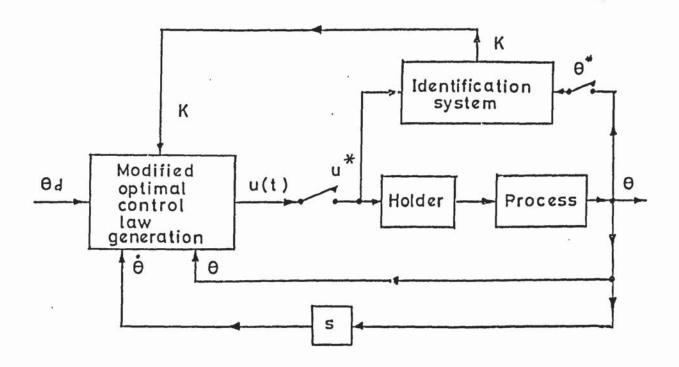
identification tank which followed the first order control tank to identify process gain accurately in spite of unknown load changes. An identification control adaptive system can be designed to maintain control loop gain within the system's limits, thus maintaining good control characteristics.

The disadvantage of such a procedure is the necessary duplication of equipment and the necessity of driving the identification flow system output in both directions from the control set-point.

Chao and Huang (67) proposed a method for the optimal design of adaptive control systems which consisted of three parts. First, an optimal control law of the time invariant process is derived. Second, Z- transform and least square techniques are used to develop an identification method which treats the time-varying gain of a second order process. Finally the above two parts are combined to design an adaptive control system which not only adapts to changes of environment but also keeps the system approaching the optimal state.

The results of analog computer simulation of optimal control and digital computer simulation of adaptive control are given. The effects of sampling time and weight factor on stability of the adaptive control system are discussed briefly (Fig. 2.7).

In this report, the authors have introduced a more important concept: instead of adjustment of parameters of a conventional PID controller by modification of the optimal control law, an extension of such a concept using a new



· Figure 2.7 Optimal adaptive control by identification

algorithm and theory of so called "Optimal Model Reference
Adaptive Control" is developed in this research (see Section
2.6 and Chapter 3).

2.4.3. System Characteristics and Optimization Adaptive Control Systems (Class 3)

There are three articles (68-70) in which the sinusoidal perturbation method is applied for adaptive control, and the final article (71) studied an optimal sensitivity and adaptive control system.

Box and Chanmugam (68) proposed a method of adaptive optimization in which the operating conditions are continuously modified by the sinusoidal perturbation method, so as to be at the optimal level at all times. Starting from a simple concept of evolutionary operation, an analogous method is developed. A detailed analysis of the effects of process dynamics in the case of a consecutive reaction system is given.

Hoyer, White, Foley and Altpeter (69) gave the general theory underlying multivariable sinusoidal perturbation adaptive optimization (SPAO). Process characteristics which indicate possible SPAO application are designated and techniques pertinent to the application of SPAO in chemical process control are discussed. The influence of the nature of the response surface and disturbance characteristics of dynamic behaviour of an extremum seeking adaptive optimizer is examined. System modifications which may yield

significant improvement in overall optimizer performance are delineated.

These techniques have been successfully applied to two pilot plants, a gas fired furnace and a fixed bed catalytic reactor, thus conclusively demonstrating the efficiency of this variant of adaptive optimization.

Price and Rippin (70) also applied the sinusoidal perturbation method of extremum seeking to an actual laboratory scale chemical process. The principle differences between this work and that carried out at Wisconsin (69) are the form of objective function used and the dynamics of the system are also more complicated. The process can be made to follow automatically changes in the position of the best operating point if a continuous estimate of the gradient of the objective function with respect to each controller variable is available. These gradients were estimated from the response of the system to sinusoidal perturbations in the controller process variables about the current operating point. The digital computer simulation was used, and the contour plots were prepared using the off-line mode.

Weinrich and Lapidus (71) proposed two general approaches to examine the sensitivity of optimal control systems to parameter variation. The first for open-loop systems involves augmenting the performance index with sensitivity terms and minimising the combined index. The second approach, an adaptive-type controller, involves estimating those parameter variations that have caused observed state

deviations and adjusting the control policy in response to this measurement.

In this paper the work is illustrated by numerical examples.

2.5. A summary of the current literature on adaptive control systems

Based upon the above general search of a total of forty articles in the recent literature on adaptive control systems (1962 \sim 1972), two summary tables were prepared and are systematically explained and listed below:

2.5.1. Table 2.1. A general summary of the current literature on the adaptive control system

Content of Table 2.1.:

- Column I. Classification of adaptive control system
 - (1) Model reference
 - (2) Identification
 - (3) System characteristics and optimization.
- Column II Function of system
 - (1) Process control
 - (2) Servomechanism (Engine, machine, aircraft missiles, satellite, etc.)
 - (3) General mathematics
- Column III Type of master control system
 - (1) Conventional control system
 - (2) Optimal control system

- Column IV Type of Adjusted parameters of master controller
 - (1) Gain, filter time constant, etc.(always used in servomechanism field)
 - (2) K_c, T_i, T_d, of conventional PID controller (always used in Process control field).
 - (3) Signal synthesis
 - (4) Optimal control law modifications
- Column V Major type of study
 - (1) Theoretical
 - (2) Experimental
 - (3) Both
- Column VI Results and solution
 - (1) Experimental
 - (2) Analytical
 - (3) Analogue (or Hybrid) computer
 - (4) Digital computer
 - (5) On-line computer operation.
- 2.5.2. Table 2.2. A general summary of the current literature

 of model reference adaptive control

 systems (additional information)

The following further information about model reference adaptive control systems is added:

- I. Model reference
- II. Performance index
- III. Adaptive controller.

Table 2.1. A general summary of the current literature on adaptive control systems

Reference		I II						III IV						٧				VI		
No.	1	2	3	1	2	3	1	2	1	2	3	4	1	2	3	1	2	3	4	5
31 Halbert					*								•					•		
32 Kwai		12			*		•		٠				٠						•	
33 White	*					•	•,		٠				•					•		
34 Drassler	*				4	*	٠,		٠				*					•		
35 Graupe & Cassir		-				•,	*	•			٠					•			•	
36 Pearson & Noonan	*		•		ť	٠							٠						X	
37. Wilkie & Parkins	*					•	*						*							
38 Inaloglu & Steadman	*		*	*			*			٠			٠			•				
39 Powell	*		. *			•		•			*		*					•		
40 Price	*					*							٠					٠		
41 Buxton & Powell				ľ	٠				*						٠			٠		
42 Monopoli	*					*	*				*		*							
43 Parks	*					٠	٠													
44 Monopoli	*					٠							*							
45 Osburn, Whitaker & Kezar	*					•	*		*				•							
46 Winsor & Roy	*					•														
47 Landau	*					•					•		•				•	٠		
48 Gromyko & Sankovskii						•	*.											•		
49 Gilbart Monopoli & price	*					*	*						•					•		

Table 2.1. (continued)

Reference		I			II		I	II		I	V		٧				VI		
No.	1	2	3	1	2	3	1	2	1	2	3.4	1	2	3	1	2	3	4	5
50 Shahein Ghonaimy & Shen	*					*	*		•	į.							•		
51.Womack & Watt		•				•	•		*			٠					٠		
52 Kershow		*		*			*			*		•					٠	٠	8
53 Puri		*			*		*		*			٠							
54 Obradovic		*				*	*			*		٠					٠		
55 Banham & Smith			*		•		•			٠				٠			٠		
56 Aoki			*			*		٠			•	•				•			
57 Pearson & Sarachik			*			*					•	•				•			
59 Pearson			*			*		٠			•	٠				٠			
60 Pearson			*			*	*		*			٠							
61 Marcus & Hougen							*			•		*					٠		
62 Crandall & Stevens	*						*			*				•	•				
63 Casciano & Staffin				*			*			٠		*					•		
64 Ryan & Crandall				*			*			٠		٠						•	
65 Ahlgren & Stevens				*			*			•		•						•	
66 Mållichamp Coughanowr & Koppel		*					•			•				•	•		•		
67 Chao & Huang		*					*											•	
68 Box & Chanmugam			*	*						٠		•						•	

Table 2.1. (continued)

Reference		I			I			пі		I	v			v				VI	:	
No.	1	2	3	1	2	3	1	2	1	2	3	4	1	2	3	1	2	3	4	5
69 Hoyer, White, Foley & Altpeter			*	*						*										
70 Price & Rappin			•				*			•										•
71 Weinrich & Lapidus		•	•	*		8		*				•	•						•	

Table 2.2. A general summary of current literature of model reference adaptive control systems (Additional information)

	Reference No	Model reference	Performance index	Adaptive controller
31	Halbert	desired transfer function	integral of response	systematic search
32	Kwai	l.desired damping c. desired frequency	1.equalised max. overshoot 2.equalised response area	Known range of variations
33	White	desired transfer function	$PI = \begin{cases} \frac{\partial e}{\partial k} & \text{edt} = 0 \end{cases}$	A simple criterion
34	Drassler	desired transfer function	response error	Gradient approach
35	Graupe & Cassir	desired transfer function	cost function of product square error	extrapolation technique
36	Pearson	desired transfer function	integral square error	modified gradient method
37	Wilkie & Perkins	desired dynamic equation	response error	transformed state variables
38	Inaloglu & Steadman	desired dynamic response pattern	response erfor	response pattern
39	Powell .	adapted model to estimate state dynamic and future trajectory of unknown plant	function of predicted trajectory of the system error	speed-up modeller
40	Price	desired dynamic equation	response error	accelerated gradient technique
41	Buxton & Powell	idealised air- plane behaviour	mean square error	gradient algorithm
.42	Monopoli	desired dynamic equation	response error vector	a reduction of order
43	Park	desired transfer function	response error	Liapunov function
44	Monopoli	desired transfer function	response error	Liapunov function

Table 2.2 (continued)

Re	eference No	Model reference	Performance index	Adaptive controller
45	Osburn, Whitaker & Kezar	desired transfer function	integral of error square	MIT rule generated from minimised PI
46	Winsor & Roy	desired plant equation	response error	Liapunov funcțion
47	Landau	desired dynamic equation	response error	Popov function
48	Gromyko & Sankovskii	desired dynamic equation	response error	Liapunov function with active and passive adjustment
49.	Gilbart Monopoli & Price	desired dynamic equation	response error	Modified Liapunov function
50	Shahein Ghoniamy & Shen	desired dynamic equation	response error	steepest descent path
61	Marcus & Hougen	dynamic perform- ance equation	response error	minimise PI
62	Grandall & Stevens	desired transfer function	integral of response error square	minimise PI incorporated with identification scheme
63	Casciano & Staffin	desired transfer function	response error	steady state correction from PI
64	Ryan & Crandall	desired dynamic equation	PI = J(e) t2 J = objective function	minimise PI
63	Ahlgren & Stevens	desired dynamic equation	integral response error square	minimise PI

2.6. Discussion

- 2.6.1. Most major research work an adaptive control is seen from Table 2.1 to be theoretical. Both theoretical and experimental approaches with different optimal control and optimal adaptive control operations are emphasised throughout the present research work.
- 2.6.2. From Table 2.1, there is only one article (70) on the use of on-line digital computer operation, and none on on-line hybrid computer operation which is used in the present research work as the major important activity.
- 2.6.3. From Table 2.1, there are only two articles which propose the modification of the optimal control law generated by the master control loop and using identification (Class 2)⁽⁶⁷⁾ and estimation (Class 3)⁽⁷¹⁾ respectively. However no such use in combination with model reference (Class 1) has been reported.
- 2.6.4. From Table 2.2, almost all model reference adaptive control uses some desired dynamic response equation. In the present research, the model reference adaptive control is generated by the optimal control law to form the optimal profile or optimal trajectory of the state variables.
- 2.6.5. From Table 2.2, almost every adaptive controller of model reference adaptive control is developed by different individual techniques. There is no general principle or theory upon which they are based. As an extension of the

basic concept from my previous work (See Section 2.4.2.) a general algorithm and theory of optimal model reference adaptive control systems is developed theoretically in Chapter 3.

PART I

THEORETICAL AND COMPLETE SIMULATION WORK

(CHAPTER 3 TO CHAPTER 7)

CHAPTER 3

THEORETICAL DEVELOPMENT OF GENERAL SCHEME FOR OPTIMAL MODEL REFERENCE ADAPTIVE CONTROL (OMRAC)

3.1. General algorithm and theory of OMRAC

As an extension of the basic concept for modification of optimal control law from my previous work (see 2.4.2.), a general algorithm and theory of OMRAC is shown below:

3.1.1. Algorithm

OMRAC contains two cascade optimal control systems, generated in such a way that the first optimal control system is generated with constant normal parameters as the optimal model reference scheme which produces the optimal state variable profile or trajectory (e.g. optimal concentration profile in a CSTR), while the second optimal system is generated with unmeasurable and uncontrollable changed parameters and variables of real process as the optimal adaptive control scheme which receives the optimal state variable profile from the model reference scheme as input function. Any response error between the current state variable of the real process and the model reference scheme, will force the optimal adaptive control scheme's desired performance index to be a minimum by a modified optimal control law. Thus the current process state variable will always be following the optimal model reference scheme as closely as possible.

3.1.2. Theory

OMRAC is made up from two schemes, viz: Optimal Model Reference (OMR) scheme and Optimal Adaptive Control (OAC) scheme. Thus:

- 1. The OMR scheme is generated by an optimal control law,

 m*(t) with constant parameters to generate an optimal

 state variable profile or trajectory, of r(t) as OMR.
- 2. The OAC scheme is generated by a modified optimal control law, U*(t) with constant parameters to minimise the function of 0 r(t) 0(t) in the presence of unmeasurable changed parameters, and:

$$U^*(\dot{T}) = m^*(t) + \phi^*(t)$$
 (3-1)

where ϕ *(t) is the derived optimal PID control law Optimal PID control law in"WEAK FORM":

$$\Phi^{*}(t) = \sum_{i=1}^{n-1} \alpha_{i} (C,K,P^{*}) \left(\theta_{i}^{r}(t) - \theta_{i}(t)\right)$$

$$+ \sum_{i=1}^{n-1} \beta_{i} (C,K,P^{*}) \int_{t_{0}}^{t_{f}} \left(\theta_{i}^{r}(t) - \theta_{i}(t)\right) dt$$

$$+ \sum_{i=1}^{n-1} \gamma_{i} (C,K,P^{*}) \frac{d}{dt} \left(\theta_{i}^{r}(t) - \theta_{i}(t)\right) (3-2)$$

Optimal PID control law in "STRONG FORM":

$$\phi^{*}(t) = \left(\phi^{*}(t)\right) \text{ weak form}$$

$$+ \sum_{i=1}^{n-1} \Delta_{P} \Delta_{\theta_{i}} \left(\frac{\partial \alpha_{i}}{\partial_{P}}\right)_{P=P^{*}} + \int_{t_{0}}^{t_{f}} \left(\sum_{i=1}^{n-1} \Delta_{P} \Delta_{\theta_{i}} \left(\frac{\partial \beta_{i}}{\partial_{P}}\right)_{P=P^{*}}\right) dt$$

$$+ \sum_{i=1}^{n-1} \left(\frac{\partial \gamma_{i}}{\partial_{P}}\right)_{P=P^{*}} \frac{d}{dt} \left(\Delta_{P} \Delta_{\theta_{i}}\right)$$

$$(3-3)$$

where o i = n state process variables in the presence of unmeasurable changed paramaters

di, Bi, 7i = optimal control law coefficients

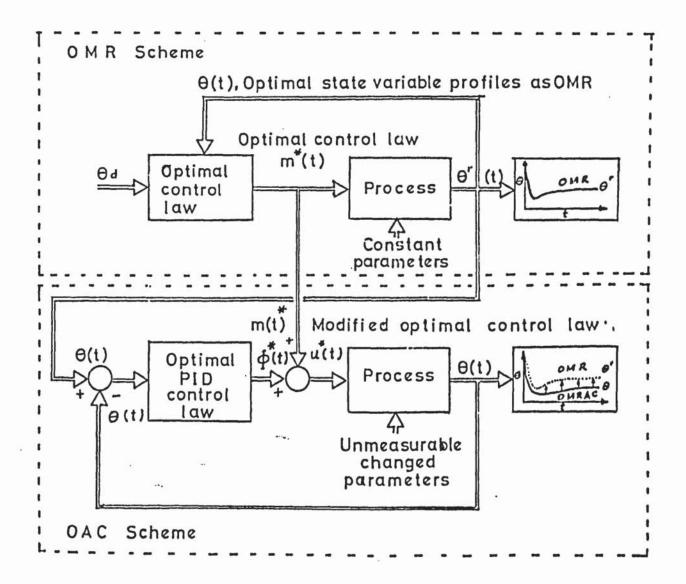
C = all constants

K = all weighting factors

and P* = all constant normal parameters

Based upon the above algorithm and theory, a general scheme and mechanism on OMRAC is established (see Fig. 3.1).

A brief comparison of the above developed OMRAC with the general type of model reference adaptive control (MRAC) is shown in Figs. 2.3 and 2.6. from the literature survey and in the following table:



OMR Scheme + OAC Scheme =>
OMRAC Scheme

Figure 3.1 General scheme of optimal model
reference adaptive control
(OMRAC)

Table 3.1. A brief comparison between OMRAC and MRAC

	~	MRAC	OMRAC
1.	General Principle	Usually there is no general principle or theory upon which they are based	A general theory for n-state variable process has been developed in the present work
2.	Model reference	Usually designed for a desired transfer function	Designed by OMR scheme
3.	Adaptive system	Usually designed to adjust the conventional PID controller's parameters	Designed by OAC scheme with modified optimal PID control laws
4.	Overall control system	Usually designed by conventional feed-back control loop	Designed by two cascade optimal control loops
	-		

3.2. Optimal Control System.

Let the general process equations containing two state variables be:

$$\frac{d\theta_1}{dt} = f_1(\theta_1, \theta_2, \theta_{L1}, \theta_{L2}, m_1, m_2)$$
 (3-5)

$$\frac{d\theta_{2}}{dt} = f_{2} (\theta_{1}, \theta_{2}, \theta_{L1}, \theta_{L2}, m_{1}, m_{2})$$
 (3-6)

where θ_1 , θ_2 = state variables θ_{L1} , θ_{L2}^{T} = load variables θ_{L1} , θ_{L2}^{T} = control variables

with initial and final conditions:

$$\theta_{1}(t_{0}) = \theta_{10}, \theta_{2}(t_{0}) = \theta_{20}$$
 (3-7-1)

$$\mathbf{o}_{1}(t_{f}) = \mathbf{o}_{1f}, \mathbf{o}_{2}(t_{f}) = \mathbf{o}_{2f}$$
 (3-7-2)

The process is controlled and operated always at its steady state conditions: $(\theta_1(t_f), \theta_2(t_f))$ or $(\theta_{1f}, \theta_{2f})$.

Let the performance index be:

$$J_{(m_1, m_2)} = \int_{t_0}^{t_f} F_{(\theta_1, \theta_2, \theta_{L1}, \theta_{L2}, m_1, m_2)} dt$$
 (3-8)

control variables m_l and m₂ are subject to the following constraints:

$$| \mathbf{m}_1 | \leqslant \mathbf{M}_1 \tag{3-9-1}$$

$$|\dot{m}_2| \leqslant M_2 \tag{3-9-2}$$

Define the functional equation:

$$f(\theta_1, \theta_2) = \min_{(m_1, m_2)} \left(J(m_1, m_2) \right)$$
 (3-10)

or

$$f(\mathbf{e}_1, \mathbf{e}_2) = J(\mathbf{m}_1^*, \mathbf{m}_2^*)$$

$$= \int_{t_0}^{t_f} F(\theta_1, \theta_2, \theta_{L1}, \theta_{L2}, m_1^*, m_2^*) dt$$
 (3-11)

where :

 $f(\theta_1, \theta_2) = minimum performance index, a function of state variables, subject to the process equations (3-5) and (3-6) with boundary conditions (3-7) and generated by the optimal control law <math>\binom{m_1^*, m_2^*}{}$

 m_1^* m_2^* = the optimal control law and is derived by any optimal control technique - maximum principle (72=74) and dynamic programming (74-76) are suggested here - and is a function of current state variables θ_1 , θ_2 , load variables θ_{L1} , θ_{L2} , and subject to the constraints shown below

$$m_1^* = m_1^* (\theta_1, \theta_2, \theta_{L1}, \theta_{L2})$$
 (3-12)

$$m_2^* = m_2^* (\theta_1, \theta_2, \theta_{L1}, \theta_{L2})$$
 (3-13)

Substituting the optimal control law into process equations (3-5) and (3-6), solving and eliminating time t, the optimal phase plane trajectory $\left[\theta_1^*(t); \theta_2^*(t)\right]$ for any fixed boundary condition is determined and shown in Fig.3.2.

3.3. Optimal model reference (OMR) Scheme

According to Theory I statement: OMR is generated by an optimal state variable profile or trajectory. Which one should be used as OMR is discussed in detail.

The optimal control system is in optimality only when all parameters in the system are unchanged but for most chemical processes in operation, the unmeasurable parameters (or

uncontrolled variables) are always changed (see 2.1.1.). Then
the new optimal phase plane trajectory will differ from the
original one, and there is a close relation between state variables
and parameters at final steady state, that is:

$$\theta_1(t_f) = h \left[\theta_2(t_f); c_1, c_2, --- c_r; P_1, P_2, ----P_g \right]$$
 (3-14)

where:

$$\theta_1(t_f), \theta_2(t_f) = \theta_{1s}, \theta_{2s} = \text{final steady state}$$
variables

$$C_1, C_2, ---C_r = constants$$

$$P_1, P_2, ---P_s = parameters.$$

From equation 3-14, it is clear that, due to unmeasurable changed parameters, $\theta_2(t_f)$ must be changed when it is desired that $\theta_1(t_f)$ should be kept constant and vice-versa.

For a CSTR, the final steady state is shown in equation (3-15).

$$C_{s} = \frac{F C_{o}}{F + aVAe^{-E/RT}s}$$
 (3-15)

where:

C_s, T_s = reactor concentration and temperature at final steady state as state variables

V,E,R = constants

F,a = inlet charge flowrate and catalyst activity
as parameters

 C_0 = Inlet concentration as load variable.

For any change in F, a or C_0 , the reactor steady state temperature must change to maintain constant reactor steady state concentration C_s which is the object of the control and T_s cannot be predicted before the load and/or parameter changes are known. This is illustrated in Fig.3.3.

From Fig. 3.3 a CSTR usually contains two optimal paths (C*, T*), and when unmeasured parameters change, T mustchange to maintain C on its original optimal path (C*). So for a two state variable process, OMR is a single optimal state variable profile or optimal concentration profile in a CSTR (See Fig. 3.4).

In general for an N state variable process, OMR has N-1

(maximum) individual optimal state variable profile, or a single

N-1 (maximum) state variable trajectory.

Thus:

- 1. If N = 2 N -1 = 1 (maximum), and then OMR is only a
 single optimal profile (Fig. 3.4).
- 2. If N = 3 N 1 = 2 (maximum), and then OMR can be one or two optimal profiles according to the number of θ^r used in the function equation of the OAC scheme (equation 3-22) or a two state variable trajectory (Fig.3.5).

For on-line computer control, when an optimal phase plane trajectory is used as the OMR scheme, there is no real time problem between the time response of the real process operation and the computer operation, because time has been eliminated from the trajectory (Fig. 3.5). However when an optimal state variable profile is used as the OMR scheme, since there is time response,

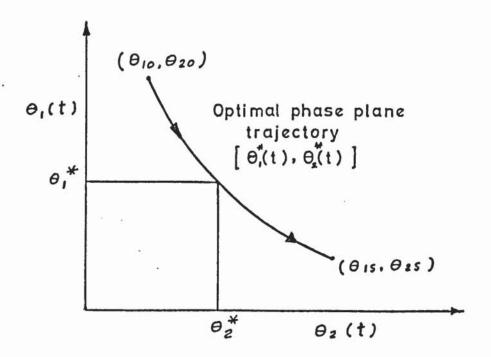


Figure 3.2 Optimal phase plane trajectory

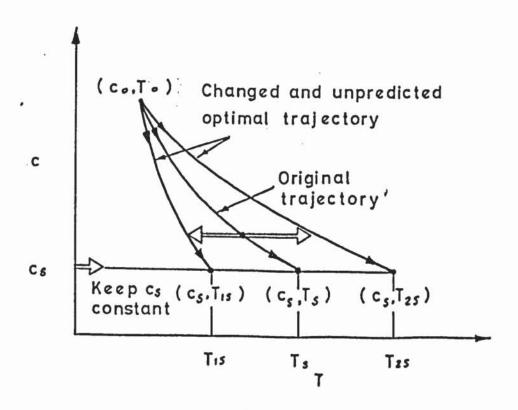


Figure 3.3 Changed and unpredicted optimal phase plane trajectory

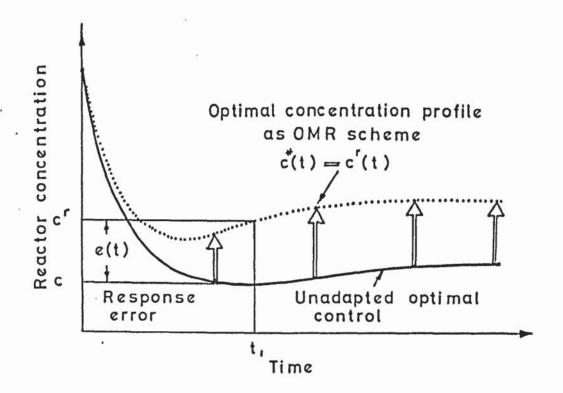


Figure 3.4 Optimal state variable profile
as OMR scheme

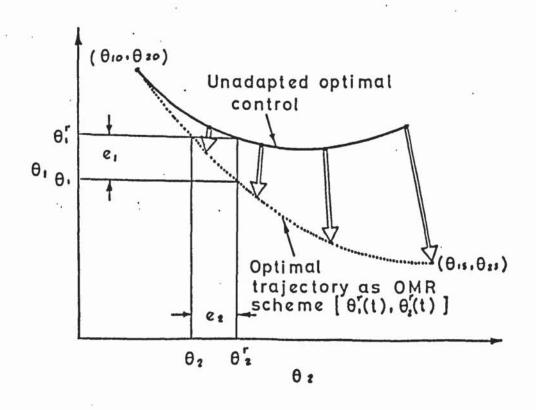


Figure 3.5 Optimal phase plane trajectory as OMR scheme

the real time problem must be carefully considered. That means the state variable from the model reference must be synchronised with the same state variable measured from the real process operation and this is the chief difference between them. In the present research work by using Hybrid and analogue computers for on-line control, real-time operation will be produced by putting the time scale factor equal to unity and measuring in seconds.

3.4. Optimal adaptive control (OAC) scheme

A second optimal control system was generated and called the OAC scheme. The OMR scheme either from optimal trajectory or from optimal profile can be treated as the set-point input of the OAC scheme. Any response error of the current state variables from OMR due to unmeasurable changed parameters for other uncontrollable variables will be forced by the OAC scheme to the minimum of a given desired performance index by a modified optimal control law.

The OAC scheme is developed in detail in the following section.

3.4.1. Modified optimal control law by "Optimal P"

Let the system equations be the same as for the OMR scheme

$$\frac{d\theta_{1}}{dt} = f_{1}(\theta_{1}, \theta_{2}, \theta_{L1}, \theta_{L2}, U_{1}, U_{2})$$
 (3-16).

$$\frac{d\theta_2}{dt} = \mathbf{f}_1 (\theta_1, \theta_2, \theta_{L1}, \theta_{L2}, \mathbf{u}_1, \mathbf{u}_2)$$
 (3-17)

where:

0 1, 0 = state variables

Θ_{I,1}, Θ_{I,2} = load variables

 U_1 , U_2 = control variables

with initial and final conditions the same as for the OMR scheme,

i.e.
$$\theta_1(t_0) = \theta_{10}, \theta_2(t_0) = \theta_{20}$$
 (3-18-1)

$$\theta_{1}(t_{f}) = \theta_{1f}, \theta_{2}(t_{f}) = \theta_{2f}$$
 (3-18-2)

The process is controlled to follow the input from the OMR scheme and finally is operated at its steady state conditions: $(\theta_1(t_f), \theta_2(t_f))$, or $(\theta_{1f}, \theta_{2f})$.

From (3.3) actually only one state variable either e_1^r or e_2^r will be selected, according to which one is desired to be controlled and used for the OMR scheme. Here let e_1^r be that selected for OMR:

Then the performance index will be

$$J(U_1, U_2) = \int_{t_0}^{t_f} (\theta_1^r, \theta_1, \theta_{21}, \theta_{22}, U_1, U_2) dt$$
 (3-19)

with U_1 and U_2 subject to the same constraints as in the OMR scheme:

$$| U_1 | \leqslant M_1 \tag{3-20-1}$$

$$| U_2 | \leq M_2$$
 (3-20-2)

Define the equation

$$f(\theta_1, \theta_1^r) = \min_{(U_1, U_2)} \left[J(U_1, U_2) \right]$$
 (3-21)

or

$$f(\theta_{1}, \theta_{1}^{r}) = J(U_{1}^{*}, U_{2}^{*})$$

$$= \int_{t_{0}}^{t_{f}} F(\theta_{1}, \theta_{1}^{r}, \theta_{L1}, \theta_{L2}, U_{1}^{*}, U_{2}^{*}) dt$$
(3-22)

where

f (θ_1, θ_1^r) = the minimum performance index, a function of the state variable θ_1 , and the state input variable θ_1^r , subject to the process equations (3-16) and (3-17) with boundary conditions (3-18) generated by the derived optimal control law (U_1^*, U_2^*) .

U1*, U2* = the optimal control law of the OAC scheme,
which is derived by any optimal control
technique and is a function of the current
state variables, input variable, load
variables, and unmeasurable changed parameters,
is subject to the constraints (3-20) and is
shown below:

$$U_1^* = U_1^* (\theta_1^r; \theta_1, \theta_2; \theta_1, \theta_2; P_1, P_2, ---P_r)$$
 (3-23)

$$U_2^* = U_2^* (\theta_1^r; \theta_1, \theta_2; \theta_1, \theta_2; P_1, P_2, ----P_r)$$
 (3-24)

where P_1 , P_2 ,--- P_r are the unmeasurable changed parameters. The theoretical approach of the modified optimal control

law is derived in detail as follows:

Following Denn and Douglas (77), the optimal control law of a two state variable set of linearised process equations subject to a quadratic objective function within fixed boundary conditions and derived by the maximum principle is:

$$U^{*}(t) = -\alpha_{1} \theta_{1}(t) - \alpha_{2} \theta_{2}(t) \qquad (3-25)$$

where

0 (t) = current state variable

 $\theta_{2}(t)$ = current state variable

 α_1 = optimal control law coefficient = $\alpha_1(C,K,P)$

 α_2 = optimal control law coefficient = $\alpha_2(C,K,P)$

. C = all process constants

K = all weighting factors used in the objective function

P = all process parameters (in the present case P is constant)

The above form of optimal control law has also been shown by Tou (79) but was derived by Dynamic Programming.

Extension of equation (3-25) in general form with n state variables (n-1) selected input variables, load variables and with unmeasurable changed parameters, leads to the following general form:

$$U^{*}(t) = -\left[\sum_{i=1}^{n} \alpha_{i} \theta_{i}(t) + \sum_{i=1}^{n-1} \beta_{i} \theta_{i}^{r}(t) + \sum_{i=1}^{n} \gamma_{i} \theta_{Li}(t)\right]$$
(3-26)

where:
$$\alpha_{i} = \alpha_{i}(C, K, P)$$
 $i = 1, 2, ----n$ (3-27-1)

$$\beta_{i} = \beta_{i}(C, K, P) \quad i = 1, 2, ----n-1$$
 (3-27-2)

$$\gamma_{i} = \gamma_{i}(C, K, P) \quad i = 1, 2, ---$$
 (3-27-3)

 $\alpha_i, \beta_i, \gamma_i$ are the optimal control law coefficients determined by the maximum principle and shown in Chapter 4 in detail

when:
$$\Theta_{i}(t) = \Theta_{i}^{r}(t)$$
 i = 1,2,--n-1, $t_{o} \le t \le t_{f}$ (3-28)

then the response of the OAC scheme is the same as the same process and boundary conditions which leads to the same optimal control law (see equations (3-1) and (3-2))

$$\left(U^{*}(t)\right)_{\theta_{i}(t) = \theta_{i}^{r}(t)} = m^{*}(t)$$
(3-29)

then equation (3-26) becomes:

$$\begin{pmatrix}
U^{*}(t) \\
\theta_{i}(t) = \theta_{i}^{r}(t)
\end{pmatrix} = -\begin{pmatrix}
\sum_{i=1}^{n-1} (\alpha_{i} + \beta_{i}) \theta_{i}^{r}(t) + \sum_{i=1}^{n} \gamma_{i} \theta_{Li}(t) \\
+ \alpha_{n} \theta_{n}(t)
\end{pmatrix} = m^{*}(t)$$
or
$$m^{*}(t) + \sum_{i=1}^{n-1} (\alpha_{i} + \beta_{i}) \theta_{i}^{r}(t) = -\begin{pmatrix} \alpha_{i} \theta_{n}(t) + \sum_{i=1}^{n} \gamma_{i} \theta_{Li}(t) \\
+ \alpha_{n} \theta_{n}(t) + \sum_{i=1}^{n-1} (\alpha_{i} + \beta_{i}) \theta_{i}^{r}(t)$$
(3-30)

substituting equation (3-30) into equation (3-26) gives:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$
(3-31)

where $\theta_{i}^{r}(t) - \dot{\theta}_{i}(t) = e_{i}(t)$

= response error

$$\alpha_{i} = \alpha_{i}(C,K,P)$$
 (3-27-1)

Let: $P = P^* + \Delta P$

where: P = unmeasurable changed parameters

P* = parameters at normal value or value at steady state condition

ΔP = change of parameters or perturbation of parameters from their normal value

Then equation (3-27-1) becomes:

$$\alpha_{i} = \alpha_{i}(C, K, P^* + \Delta P) \qquad (3-32)$$

By a Taylor's series expansion and omitting the second and higher order terms, equation (3-32) becomes:

$$\alpha_{i} = \alpha (C, K, P^{*}) + \Delta P \left(\frac{\partial di}{\partial P}\right)_{P=P^{*}}$$
 (3-33)

Substituting equation (3-33) into equation (3-31) gives:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i}(C, K, P^{*}) \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \Delta P \Delta \theta_{i} \left(\frac{\partial d_{i}}{\partial P} \right)_{P=P^{*}}$$
(3-34)

In equation (3-34), the term $\Delta P \Delta \theta_i$ is a second order perturbation; if the unmeasurable changed parameter is within a certain range of the normal value, the last term of equation (3-34) can be justifiably omitted. Then the theoretical approach of the modified optimal control law for the OAC scheme will be:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} (C,K,P^{*}) \left(o_{i}^{r}(t) - o_{i}(t) \right)$$
 (3-35)

Equation (3-35) has the same form as equation (3-31) except for the change of P to P*.

Equation (3-35) states that: the difference between the optimal control law of the OAC scheme and the optimal control law of the OMR scheme is proportional to the response error, and all the coefficients α_i will be determined with constant normal parameters.

Also since equation (3-35) is very similar to conventional proportional control, this modified optimal control law will be called "Optimal P".

3.4.2. Modified optimal control law by "Optimal P * I"

By using the same approach, the modified optimal control law can be derived for more complicated forms, just the same as the conventional controller modes.

In the literature, only Shih (79) introduced the integral action into optimal control. Here it has been derived by a different kind of approach and has been extended to all combinations of the Optimal PID system and the full complications of the theoretical approach have been applied in the subsequent work on complete simulation and on-line computer control operation (see Chapter 7 and Part II).

Let the general form of optimal control law be:

$$U^{*}(t) = -\left(\sum_{i=1}^{n} \alpha_{i} \theta_{i}(t) + \sum_{i=1}^{n-1} \beta_{i} \theta_{i}^{r}(t) + \sum_{i=1}^{n} \tau_{i} \theta_{Li}(t) + \sum_{i=1}^{n-1} \tau_$$

where
$$d_{i} = d_{i} (C,K,P) i = 1,2,---n$$
 (3-37-1)

$$\beta_{i} = \beta_{i} (C, K, P) \quad i = 1, 2, ----n-1 \quad (3-37-2)$$

$$\gamma_{i} = \gamma_{i} (C, K, P) i = 1, 2, --- (3-37-3)$$

$$\delta_{i} = \delta_{i} (C, K, P) \quad i = 1, 2, ---n-1 \quad (3-37-4)$$

All α_i , β_i , γ_i and δ_i the optimal law coefficients can be determined by the maximum principle as shown in Chapter 5 in detail.

When
$$\theta_{i}(t) = \theta_{i}^{r}(t)$$
; $i = 1, 2, ----n-1$; $t_{0} \le t \le t_{f}$

$$\left(U^{*}(t)\right)_{\mathbf{e}_{\underline{i}}(t) = \mathbf{e}_{\underline{i}}^{r}(t)} = m^{*}(t)$$

$$= -\left(\sum_{\underline{i}=\underline{1}}^{n-1} (\mathbf{e}_{\underline{i}} + \mathbf{h}_{\underline{i}}) \mathbf{e}_{\underline{i}}^{r}(t) + \sum_{\underline{i}=\underline{1}}^{r} \boldsymbol{\tau}_{\underline{i}} \mathbf{e}_{\underline{L}\underline{i}}(t) + \boldsymbol{\alpha}_{\underline{n}} \mathbf{e}_{\underline{n}}(t)\right) \qquad (3-38)$$

Hence

$$m^{*}(t) + \sum_{i=1}^{n-1} (\alpha_{i} + \beta_{i}) \theta_{i}^{r}(t) = -\left(\sum_{i=1}^{r} \tau_{i} \theta_{Li} + \alpha_{n} \theta_{n}(t)\right)$$
(3-59)

Substituting equation (3-39) into equation (3-36) and simplifying:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \int_{t_{0}}^{t_{f}} \delta_{i} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right) dt \qquad (3-40)$$

Let

$$P = P^* + \Delta P$$

Then
$$\alpha_{i} = \alpha_{i} (C, K, P^* + \Delta P)$$
 (3-41-1)

$$\delta_{i} = \delta_{i} (C, K, P^* + \Delta P)$$
 (3-41-2)

Expansion of equation (3-41) by a Taylor's series and neglecting the second and higher order terms:

$$\alpha_{i} = \alpha_{i}(C, K, P^{*}) + \Delta P \left(\frac{\partial \alpha_{i}}{\partial P}\right)_{P=P^{*}}$$

$$\delta_{i} = \delta_{i}(C, K, P^{*}) + \Delta P \left(\frac{\partial \delta_{i}}{\partial P}\right)_{P=P^{*}}$$
(3-42-1)

Substituting equation (3-42) into equation (3-40) gives:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i}(C,K,P^{*}) \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} i^{(C,K,P^{*})} \int_{t_{0}}^{t_{f}} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right) dt$$

$$+ \left(\sum_{i=1}^{n-1} \Delta P \Delta \theta_{i} \frac{\partial \alpha_{i}}{\partial P} \right)_{P=P^{*}} + \int_{t_{0}}^{t_{f}} \left(\sum_{i=1}^{n-1} \Delta P \Delta \theta_{i} \left(\frac{\partial \delta_{i}}{\partial P} \right) \right)_{P=P^{*}} \right) dt$$

$$(3-43)$$

In equation 3-44), neglecting the second order perturbation terms, the theoretical approach of the modified optimal control law for the OAC scheme will be:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} (C,K,P^{*}) \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \delta_{i} (C,K,P^{*}) \int_{t_{0}}^{t_{f}} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right) dt$$

$$(3-44)$$

15 . .

Equation (3-44) has the same form as equation (3-40) except for the change of P to P*.

Equation (3-44) states that: the difference between the optimal control law of the OAC scheme and the optimal control law of OMR scheme is proportional to the response error and its integral and all the coefficients $\boldsymbol{\alpha}_i$ and $\boldsymbol{\delta}_i$ will be determined with constant normal parameters.

Also equation (3-44) is very similar to conventional P + I control and so this modified optimal control law will be called "Optimal P + I".

3.4.3. Modified optimal control law by "Optimal P + I + D"

Let the general form of optimal control law be:

$$U^{*}(t) = -\left(\sum_{i=1}^{n} \alpha_{i} \theta_{i}(t) + \sum_{i=1}^{n-1} \beta_{i} \theta_{i}^{r}(t) + \sum_{i=1}^{n} \gamma_{i} \theta_{Li}(t)\right)$$

$$+ \sum_{i=1}^{n-1} \int_{t_{\bullet}}^{t_{f}} \left(\theta_{i}(t) - \theta_{i}^{r}(t)\right) dt + \sum_{i=1}^{n-1} \frac{d}{dt} \varsigma_{i} \left(\theta_{i}(t) - \theta_{i}^{r}(t)\right)\right)$$

$$(3-45)$$

where:

$$d_i = d_i(C,K,P)$$
 $i = 1,2,---n$ (3-46-1)

$$\beta_{i} = \beta_{i}(C,K,P) \quad i = 1,2,---n-1$$
 (3-46-2)

$$r_i = r_i(C, K, P)$$
 $i = 1, 2, ---- v$ (3-46-3)

$$\delta_{i} = \delta_{i}(C,K,P) \quad i = 1,2,---n-1$$
 (3-46-4)

$$\mathbf{g}_{i} = \mathbf{g}_{i}(C,K,P) \quad i = 1,2,---n-1$$
 (3-46-5)

All α_i , β_i , γ_i , δ_i , and ξ_i , the optimal law coefficients can be determined by the maximum principle and is shown in Chapter 5 in detail.

When:
$$\theta_{i}(t) = \theta_{i}(t)$$
; $i = 1, 2, ----n-1t_{0} \le t \le t_{f}$

$$\begin{bmatrix} U^*(t) \\ \theta_{\underline{i}}(t) = \theta_{\underline{i}}^{r}(t) \end{bmatrix} = m^*(t)$$

$$= - \begin{pmatrix} n-1 \\ \sum_{i=1}^{n-1} (\alpha_{\underline{i}} + \beta_{\underline{i}}) \theta_{\underline{i}}^{r}(t) + \sum_{i=1}^{n} \gamma_{\underline{i}} \theta_{\underline{L}\underline{i}}(t) + \alpha_{\underline{n}} \theta_{\underline{n}}(t) \end{pmatrix} (3-47)$$
or $m^*(t) + \sum_{i=1}^{n-1} (\alpha_{\underline{i}} + \beta_{\underline{i}}) \theta_{\underline{i}}^{r}(t) = - \begin{pmatrix} v \\ \sum_{i=1}^{n} \gamma_{\underline{i}} \theta_{\underline{L}\underline{i}}(t) + \alpha_{\underline{n}} \theta(t) \end{pmatrix} (3-48)$

Substituting equation (3-48) into equation (3-45) and simplifying:

$$U^{*}(t) = m_{i}^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \int_{t_{0}}^{t_{f}} \delta_{i} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right) dt$$

$$+ \sum_{i=1}^{n-1} \frac{d}{dt} \xi_{i} \left(\theta_{i}^{r}(t) - \theta_{i}(t) \right)$$

$$(3-49)$$

Let: $P = P^* + \Delta P$

$$\alpha_{i} = \alpha_{i}(C, K, P^{*} + \Delta P)$$
 (3-50-1)

$$\delta_{i} = \delta_{i}(C, K, P^* + \Delta P)$$
 (3-50-2)

$$\xi_{i} = \xi_{i}(C, K, P^* + \Delta P)$$
 (3-50-3)

Expansion of equation (3-50) by a Taylor's series and neglecting the second and higher order terms:

$$\lambda_{i} = \alpha_{i}(C, K, P^{*}) + \Delta P \left(\frac{\partial \alpha_{i}}{\partial P}\right)_{P=P^{*}}$$
(3-51-1)

$$\delta_{i} = \delta_{i}(C,K,P^{*}) + \Delta_{i}P\left(\frac{\partial \delta_{i}}{\partial P}\right)_{P=P^{*}}$$
 (3-51-2)

$$\zeta_{i} = \zeta_{i}(C,K,P^{*}) + \Delta P \left(\frac{\partial \zeta_{i}}{\partial P}\right)_{P=P^{*}}$$
(3-51-3)

Substituting equation (3-51) into equation (3-49) gives:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} (C, K, P^{*}) \left(\mathbf{e}_{i}^{r}(t) - \mathbf{e}_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \delta_{i}(C, K, P^{*}) \int_{t_{0}}^{t} \left(\mathbf{e}_{i}^{r}(t) - \mathbf{e}_{i}(t) \right) dt$$

$$+ \sum_{i=1}^{n-1} \zeta_{i}(C, K, P^{*}) \frac{d}{dt} \left(\mathbf{e}_{i}^{r}(t) - \mathbf{e}_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \Delta P \Delta \mathbf{e}_{i} \left(\frac{\partial \alpha_{i}}{\partial P} \right)_{P=P^{*}} + \int_{t_{0}}^{n-1} \Delta P \Delta \mathbf{e}_{i} \left(\frac{\partial \delta_{i}}{\partial P} \right)_{P=P^{*}} dt$$

$$+ \sum_{i=1}^{n-1} \left(\frac{\partial \zeta_{i}}{\partial P} \right)_{P=P^{*}} \frac{d}{dt} \left(\Delta P \Delta \mathbf{e}_{i} \right)$$

$$(3-52)$$

In equation (3-52), neglecting the second order perturbation terms, then the theoretical approach of the modified optimal control law for the OAC scheme will be:

$$U^{*}(t) = m^{*}(t) + \sum_{i=1}^{n-1} \alpha_{i} (C,K,P^{*}) \left(\boldsymbol{\theta}_{i}^{r}(t) - \boldsymbol{\theta}_{i}(t) \right)$$

$$+ \sum_{i=1}^{n-1} \delta_{i} (C,K,P^{*}) \int_{t_{0}}^{t_{f}} \left(\boldsymbol{\theta}_{i}^{r}(t) - \boldsymbol{\theta}_{i}(t) \right) dt$$

$$+ \sum_{i=1}^{n-1} \zeta_{i} (C,K,P^{*}) \frac{d}{dt} \left(\boldsymbol{\theta}_{i}^{r}(t) - \boldsymbol{\theta}_{i}(t) \right)$$

$$(3-53)$$

Equation (3-53) has the same form as equation (3-40) except for the change of P to P*.

Equation (3-53) states that: the difference between the optimal control law of the OAC scheme and the optimal l_{aw} of the OMR scheme is proportional to response error, its integral and its derivative and all the coefficients α_i , δ_i and δ_i will be determined with constant normal parameters.

Also equation (3-53) is very similar to conventional P + I + D control, and so this modified optimal control law will be called "Optimal P + I + D".

3.4.4. Discussion

- (1) Equations (3-35), (3-44) and (3-53) are modified optimal control laws represented by "Optimal P, P + I and P + I + D" respectively. Since the second order perturbation terms have been neglected, they may be called "Weak Form" of the modified optimal control law.
- (2) Equations (3-34), (3-43) and (3-52) are also modified optimal control laws represented by "Optimal P, P + I and P + I + D" respectively. Since they contain the second order perturbation terms, they may be called "Strong Form" of the modified optimal control law.
- (3) Because of the presence of unmeasurable changed parameters the comparatively weak form can easily be developed and operated. Hence the "weak form" was used throughout this research work.

CHAPTER 4

MATHEMATICAL DERIVATION OF THE OMR SCHEME FOR A CONTINUOUS STIRRED TANK REACTOR (C.S.T.R.).

4.1. Assumptions for the derivation

For justification of the mathematical derivation of a partially simulated CSTR, all assumptions used are the same as in Buxton's Ph.D.Thesis (80) and are listed below:

- (1) The partially simulated CSTR is designed and based on a simple non-reversible first order exothermic chemical reaction.
- (2) Water in the reactor is well mixed by a mixer whose speed is adjusted by a variac.
- (3) Since the operating temperature of the reactor is only about 30°C, heat losses from reactor to vessel to surroundings are neglected.
- (4) Since the percentage of total heat absorbed by the immersion heater coil is about 1% of the input to the reactor, then the immersion heater time lag is neglected.
- (5) Since the time delay in the cooling coil is about 1.3 sec. for 10 litre/min flowrate, then time delay in the cooling coil is neglected. Actually by using an additional new electric temperature transmitter for outlet cooling coil to give a direct ΔT measurement (refer to PartII) this effect of time delay in the cooling has been eliminated.
- (6) Since the time constant in the coding coil is below

 1.0 sec. for 10 litre/min flow mate, then the time constant
 in cooling coil is neglected.

- (7) Since the changing of the control valve with positioner from fully closed to fully open takes about 5 sec. the time delay in the control valve is neglected.
- (8) Since electrical measurement devices both for temperature and flow are used, the time delay is always less then 1 sec., and these are neglected.
- (9) Since all interface signals used between the computers and process are electrical the time delay between them is neglected.

The total operating time of every actual on-line operation is about 600 sec. (refer to Part II), so all the above assumptions are reasonable.

4.2. Process Mathematical model

For a simple first order non-reversible exothermic reaction in a CSTR, the dynamic material and energy equations are shown below:

$$\frac{dC}{dt} = \frac{F}{V} (C_o - C) - aAe^{-E/RT}C$$
 (4-1)

$$\frac{dT}{dt} = \frac{F}{V} (T_0 - T) + \frac{aA(-\Delta H)e^{-E/RT}C}{\rho C_p} - \frac{Q_c}{\rho C_p V}$$
 (4-2)

initial conditions:
$$C = C(t_0)$$
; $T = T(t_0)$ (4-3--1)

final conditions:
$$C = C(t_f)$$
; $T = T(t_f)$ (4-3-2)

where.

C = inlet concentration (mol/litre)

C = concentration in reactor (mol/litre)

F = inlet flowrate to reactor (litre/min)

V = reactor effective volume (lires)

a = catalyst activity (% of original value)

A = constant of Arrhenius equation (1/sec)

E = reaction energy, a constant (cal/mol)

R = gas constant (cal/mol^oK)

T = reactor temperature (°C)

T = inlet temperature(°C)

 $(-\Delta H)$ = change of enthalpy on reaction (cal/mol)

 ρ = density of reactant (g/cm³)

C_n = specific heat of reactant (cal/g.deg C)

Q = heat removed by cooling coil water (cal/sec)

In equations (4-1) and (4-2), let

state variables = C, T.

control variable = Q

load variables: C, T

parameters: a, F.

Note: In the actual on-line operation, since it is difficult to manually operate an exact step change of To, it will be kept constant, and a, F, used as the unmeasurable and uncontrollable changed parameters and Co used as the load variable.

Equations (4-1) and (4-2) are generalised as follows:

$$\frac{dC}{dt} = G(C_0, T_0, C, T, Q_c) \tag{4-4}$$

$$\frac{dT}{dt} = H(C_0, T_0, C, T, Q_c) \qquad (4-5)$$

In the research work, the optimal control law is derived from the process mathematical model linearised about the steady

state operating points by Pontryagin's maximum principle, while for complete simulation and on-line operation the original non-linear equations of the process itself (4-1), (4-2) will still be used. (See Chapters 6, 7 8 and Part II)

Linearused equations from (4-4) and (4-5) about the steady state operating point are shown below

$$\frac{d\theta_{1}}{dt} = a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1} = f_{1}(\theta_{1}, \theta_{2}, \theta_{L1}) \qquad (4-6)$$

$$\frac{d\theta_2}{dt} = a_{21}\theta_1 + a_{22}\theta_2 + d_{22}\theta_{L2} + bm = f_2(\theta_1, \theta_2, \theta_{L2}, m)$$
 (4-7)

with initial conditions

$$\theta_1(t_0) = \theta_{10} \tag{4-8-1}$$

$$\theta_2(t_0) = \theta_{20}$$
 (4-8-2)

final conditions

$$\theta_{1}(t_{f}) = \theta_{1f} \tag{4-9-1}$$

$$\theta_2(t_f) = \theta_{2f} \tag{4-9-2}$$

where

$$\theta_1 = C - C_g = A C$$
 (4-10-1)

$$\theta_2 = T - T_s = \Delta T$$
 (4-10-2)

$$\theta_{L1} = C_0 - C_{0S} = \Delta C_0$$
 (4-10-3)

$$\theta_{L2} = T_0 - T_{0S} = \Delta T_0$$
 (4-10-4)

$$m = Q_c - Q_{cs} = \Delta Q_c$$
 (4-10-5)

subscript s = steady state

$$a_{11} = \left(\frac{\partial G}{\partial C}\right)_{S} = -\frac{F}{V} - aAe^{-\frac{E}{RT_{S}}}$$
 (4-11-1)

$$a_{12} = \left(\frac{\partial G}{\partial C}\right)_{S} = \frac{aAE}{RT_{S}^{2}} + C_{S}$$
 (4-11-2)

$$d_{11} = \left(\frac{\partial G}{\partial C}\right)_{G} = \frac{F}{V} \tag{4-11-3}$$

$$a_{21} = \left(\frac{\partial H}{\partial C}\right)_{S} = \frac{aA(-\Delta H)e}{\rho C_{p}}$$
 (4-11-4)

$$a_{22} = \left(\frac{\partial H}{\partial T}\right)_{g} = -\frac{F}{V} - \frac{aA(-\Delta H)}{\rho \sigma_{p}} \left(\frac{E}{RT_{g}^{2}} - \frac{E}{RT_{g}}\right) C_{g} \quad (4-11-5)$$

$$d_{22} = \left(\frac{\partial H}{\partial T_0}\right)_S = \frac{F}{V} \tag{4-11-6}$$

$$b = \left(\frac{\partial H}{\partial Q_c}\right)_S = -\frac{1}{\rho C_p V}$$
 (4-11-7)

4.3. Optimal control system

The system will be operated by generation of an optimal concentration profile in a CSTR from any initial condition to the desired steady state with changed load variables and with constant parameters.

Since the optimal concentration profile will be generated, so the performance index is suggested as follows:

$$J_{(m)} = \int_{t_0}^{t_f} \left[K_1 (\theta_d - \theta_1)^2 + K_2 \theta_2^2 + m^2 \right] dt$$
 (4-12)

where θ_d = Set point of $\theta_1(t)$, or desired concentration of new steady state condition

 K_1 , K_2 = weighting factors

Define the functional equation

$$f(\theta_d, \theta_1, \theta_2) = \min_{(m)} \left\{ \int_{t_0}^{t_f} \left[\kappa_1(\theta_d - \theta_1)^2 + \kappa_2 \theta_2^2 + m^2 \right] dt \right\}$$

$$= \int_{t_0}^{t_f} \left[K_1(\theta_d - \theta_1)^2 + K_2 \theta_2^2 + m^{2} \right] dt \qquad (4-13)$$

Equation (4-13) is an expression of the optimal control law m*(t) which can minimise the performance index equation (4-12) and which is subject to the linearised process equations (4-6) and (4-7) with boundary conditions given by equation (4-8) and (4-9). Here we assume m is free to vary without restriction and the constraint will be discussed in the next section.

Using the maximum principle, let a new wariable $\theta_3(t)$ as performance index be introduced

$$\theta_{3}(t) = \int_{t_{0}}^{t_{f}} \left[K_{1} (\theta_{d} - \theta_{1})^{2} + K_{2} \theta_{2}^{2} + m^{2} \right] dt$$
 (4-14)

or

$$\frac{d\theta_2}{dt} = K_1 (\theta_d - \theta_1)^2 + K_2 \theta_2^2 + m^2 = f_3(\theta_d, \theta_1, \theta_2, m)$$
 (4-15)

then the original performance index becomes:

$$S(t_f) = C_3 \theta_3(t_f) \tag{4-16}$$

where S(t_f) = performance index using a different simple form

$$C_3 = \lambda_3(t_f) = 1$$
 (4-17)

 λ (t) = adjoint variable defined later

From the maximum principle a Hamiltonian equation is introduced as follows:

$$H (\theta_{1}, \theta_{2}, m, \lambda) = \sum_{i=1}^{3} \lambda_{i} f_{i}$$

$$= \lambda_{1} \left[a_{11} \theta_{1} + a_{12} \theta_{2} + d_{11} \theta_{L1} \right]$$

$$+ \lambda_{2} \left[a_{21} \theta_{1} + a_{22} \theta_{2} + d_{22} \theta_{2} + bm \right]$$

$$+ \lambda_{3} \left[k_{1} (\theta_{d} - \theta_{1})^{2} + K_{2} \theta_{2}^{2} + m^{2} \right]$$
(4-18)

where λ_1, λ_2 , and λ_3 are adjoint variables given by the following equation

$$\frac{d\lambda_{i}}{dt} = -\left(\frac{\partial H}{\partial \Theta_{i}}\right) \tag{4-19}$$

or:
$$\frac{d\lambda_1}{dt} = -\frac{\partial H}{\partial \theta_1} = -a_{11}\lambda_1 - a_{21}\lambda_2 + 2K_1(\theta_d - \theta_1)\lambda_3 \quad (4-20)$$

$$\frac{d\lambda_2}{dt} = -\frac{\partial H}{\partial \theta_2} = -a_{12}\lambda_1 - a_{22}\lambda_2 - 2K_2\theta_2\lambda_3 \qquad (4-21)$$

$$\frac{d\lambda_3}{dt} = -\frac{\delta H}{\delta \Theta_2} = 0 ag{4-22}$$

Since $\frac{d\lambda_3}{dt} = 0$, $\lambda_3(t_f) = 1$

Hence
$$\lambda_3(t) = 1$$
 (4-23)

Substituting λ_3 (t) into equations (4-18), (4-20) and (4-21) gives:

$$H(\theta_{1}, \theta_{2}, m, \lambda) = (a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1})\lambda_{1}$$

$$+ (a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2} + bm)\lambda_{2}$$

$$+ (K_{1}(\theta_{d} - \theta_{1})^{2} + K_{2}\theta_{2}^{2} + m^{2}) \qquad (4-24)$$

$$\frac{d\lambda_{1}}{dt} = -a_{11}\lambda_{1} - a_{21}\lambda_{2} + 2K_{1}(\theta_{d} - \theta_{1})$$
 (4-25)

$$\frac{d\lambda_2}{dt} = -a_{21}\lambda_1 - a_{22}\lambda_2 - 2K_2\theta_2$$
 (4-26)

The optimal control law will be determined by the condition that:

$$\frac{\partial H}{\partial m} = 0 \tag{4-27}$$

so
$$b\lambda_2 + 2m = 0$$

or $m^*(t) = -(\frac{b}{2})\lambda_2(t)$ (4-28)

Substituting equation (4-28) into equation (4-7) and rewriting equation (4-6):

$$\frac{d\theta_1}{dt} = a_{11}\theta_1 + a_{12}\theta_2 + d_{11}\theta_{L1} \tag{4-6}$$

$$\frac{d\theta_2}{dt} = a_{21}\theta_1 + a_{22}\theta_2 + d_{22}\theta_{L2} - \frac{b^2}{2}\lambda_2$$
 (4-29)

Since the boundary conditions of the state variables $\theta_1(t)$ and $\theta_2(t)$ are fixed and shown in equations (4-8) and (4-9) which are based upon steady state operation, so the boundary conditions of $\lambda_1(t)$ and $\lambda_2(t)$ will be free (73,77); or:

Initial conditions:

$$\lambda_{1}(t_{0}) = free \qquad (4-30-1)$$

$$\lambda_{2}(t_{0}) = \text{free} \qquad (4-30-2)$$

Final conditions:

$$\lambda_{1}(t_{f}) = \text{free} \qquad (4-31-1)$$

$$\lambda_{2}(t_{f}) = free \qquad (4-31-2)$$

Since both $\lambda_1(t)$ and $\lambda_2(t)$ are free boundary conditions, then $\lambda_1(t)$ and $\lambda_2(t)$ can be set to be any function between the time: $t_0 \le t \le t_f$, and subject to the equations (4-6), (4-29), (4-25) and (4-26). Hence, following Denn and Douglas (77), as an extension let the solution of $\chi(t)$ and $\chi(t)$ take the form:

$$\lambda_{1}(t) = \alpha_{11}\theta_{1}(t) + \alpha_{12}\theta_{2}(t) + \alpha_{13}\theta_{d}(t) + \alpha_{14}\theta_{L1}(t) + \alpha_{15}\theta_{22}(t)$$
(4-32)

$$\lambda_{2}(t) = \alpha_{12}\theta_{1}(t) + \alpha_{22}\theta_{2}(t) + \alpha_{23}\theta_{d}(t) + \alpha_{24}\theta_{L1}(t) + \alpha_{25}\theta_{L2}(t)$$

$$(4-33)$$

where: $\theta_1(t)$, $\theta_2(t)$, $\theta_d(t)$, $\theta_{L1}(t)$ and $\theta_{L2}(t)$ are state

wariables, desired set-point variable and load variables respectively are all measurable

and $\alpha_{11}, \alpha_{12}, \alpha_{13}, \alpha_{14}, \alpha_{15}, \alpha_{22}, \alpha_{23}, \alpha_{24}$ and α_{25} are coefficients to be determined in section 5 in detail.

Substituting $\lambda_2(t)$, into equation (4-28), the optimal control law of the OMR scheme will be:

$$m^{*}(t) = -\frac{b}{2} \left[\alpha_{12} \theta_{1}(t) + \alpha_{22} \theta_{2}(t) + \alpha_{23} \theta_{1}(t) + \alpha_{24} \theta_{L1}(t) + \alpha_{25} \theta_{L2}(t) \right]$$

$$(4-34)$$

Then solving equations (4-6) and (4-7) with known $m^*(t)$, the optimal concentration profile for OMR will be obtained as:

$$e_1^*(t) \equiv e_1^r(t)$$
 $t_0 \le t \le t_f$ (4-35)

4.4. Consideration of constraints

In the derivation of section 3, it was assumed that m*(t) was free to wary without any restriction. However m*(t) operates with the following constraints:

From equation (4-10-5):

$$m^*(t) = Q_c^* \rightarrow Q_{cs}$$

or $Q_c^*(t) = m^* + Q_{cs}$ (4-36)

where:

 Q_{CS} = Cooling coil heat removal rate at steady state $Q_{C}^{*}(\mathbf{t})$ = optimal cooling coil heat removal rate

 $Q_c^*(t)$ is limited by the cooling water flowrate which is controlled by a pneumatic control valve, i.e.

$$(Q_c)_{\min} \leq Q_c^* \leq (Q_c)_{\max}$$
 (4-37)

where:

(Q_c)_{min} = minimum heat removal rate when the control valve is closed

and $(Q_c)_{max}$ = maximum heat removal rate when the control valve is wide open

According to the statement of the maximum principle, it will be known from (72,77,78) that:

Along the minimum (or maximum) path, the Hamiltonian is stationary when the optimal control law is unconstrained, and a minimum (or maximum) when the optimal control law lies at a constraint. In other words, the necessary condition for the performance index to be at a minimum (or maximum) is that m*(t) lies in the interior of the region of m(t), or:

M_{min} < m*(t) < M_{max}

$$\frac{\partial H}{\partial m} = 0 \text{ at } m(t) = m^*(t); t_0 \leqslant t \leqslant t_f \qquad (4-38)$$

when m*(t) lies at the boundary of the constraints:

$$H = Min \text{ at } m^*(t) = M_{min}$$
 (4-39-1)

or

$$H = Max at m*(t) = M_{max}$$
 (4-39-2)

Hence $m^*(t)$ can be treated as a limiter between M_{\min} and M_{\max} .

4.5. Determination of the coefficients: α_{12} , α_{22} , α_{23} , α_{24} and α_{25} .

Differentiating equations (4-32) and 4-33), neglecting the derivatives of θ_d , θ_{L1} and θ_{L2} , and substituting equations

(4-6), (4-7) and (4-34) into the equations, gives

$$\frac{d\lambda_{1}}{dt} = \alpha_{11}(a_{11}e_{1} + a_{12}e_{2} + d_{11}e_{L1}) + \alpha_{12}\left[a_{21}e_{1} + a_{22}e_{2} + a_{23}e_{L2} - \frac{b^{2}}{2}(\alpha_{12}e_{1} + \alpha_{22}e_{2} + \alpha_{23}e_{d} + \alpha_{24}e_{L1} + \alpha_{25}e_{L2})\right]$$

$$= (a_{11}\alpha_{11} + a_{21}\alpha_{12} - \frac{b^{2}}{2}\alpha_{12}^{2})\theta_{1}$$

$$+ (a_{12}\alpha_{11} + a_{22}\alpha_{12} - \frac{b^{2}}{2}\alpha_{12}\alpha_{22})\theta_{2}$$

$$+ (d_{11}\alpha_{11} - \frac{b^{2}}{2}\alpha_{12}\alpha_{24})\theta_{L1}$$

$$+ (d_{22}\alpha_{12} - \frac{b^{2}}{2}\alpha_{12}\alpha_{25})\theta_{L1} - (\frac{b^{2}}{2}\alpha_{12}\alpha_{23})\theta_{d} \qquad (4-40)$$

$$\frac{d\lambda_{2}}{dt} = \lambda_{12}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) + \lambda_{22}\left[(a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2})\right]$$

$$- \frac{b^{2}}{2}(\lambda_{21}\theta_{1} + \lambda_{22}\theta_{2} + \lambda_{23}\theta_{d} + \lambda_{24}\theta_{L1} + \lambda_{25}\theta_{L2})$$

$$= (a_{11}\lambda_{12} + a_{21}\lambda_{22} - \frac{b^{2}}{2}\lambda_{12}\lambda_{22})\theta_{1}$$

$$+ (a_{12}\lambda_{12} + a_{22}\lambda_{22} - \frac{b^{2}}{2}\lambda_{22})\theta_{2}$$

$$+ (d_{11}\lambda_{12} - \frac{b^{2}}{2}\lambda_{22}\lambda_{24})\theta_{L1}$$

$$+ (d_{22}\lambda_{22} - \frac{b^{2}}{2}\lambda_{22}\lambda_{25})\theta_{L2} - (\frac{b^{2}}{2}\lambda_{22}\lambda_{25})\theta_{d}$$

$$(4-41)$$

Substituting equations (4-32) and (4-33) into equations (4-25 and (4-26) gives:

$$\frac{d\lambda_{1}}{dt} = -a_{11}(\alpha_{11}e_{1} + \alpha_{12}e_{2} + \alpha_{13}e_{d} + \alpha_{14}e_{L1} + \alpha_{15}e_{L2})$$

$$-a_{21}(\alpha_{12}e_{1} + \alpha_{22}e_{2} + \alpha_{23}e_{d} + \alpha_{24}e_{L1} + \alpha_{25}e_{L2})$$

$$+ 2K_{1}(e_{d} - e_{1})$$

$$= (-a_{11}\alpha_{11} - a_{21}\alpha_{12} - 2K_{1}) \theta_{1}$$

$$+ (-a_{11}\alpha_{12} - a_{21}\alpha_{22}) \theta_{2}$$

$$+ (-a_{11}\alpha_{13} - a_{21}\alpha_{23} + 2K_{1}) \theta_{d}$$

$$+ (-a_{11}\alpha_{14} - a_{21}\alpha_{24}) \theta_{L1}$$

$$+ (-a_{11}\alpha_{15} - a_{21}\alpha_{25}) \theta_{L2}$$

$$\frac{d\lambda_{2}}{dt} = -a_{12}(\alpha_{11}\theta_{1} + \alpha_{12}\theta_{2} + \alpha_{13}\theta_{d} + \alpha_{14}\theta_{L1} + \alpha_{15}\theta_{L2})$$

$$- a_{22}(\alpha_{12}\theta_{1} + \alpha_{22}\theta_{2} + \alpha_{23}\theta_{d} + \alpha_{24}\theta_{L1} + \alpha_{25}\theta_{L2})$$

$$- 2K_{2}\theta_{2}$$

$$= (-a_{12}\alpha_{11} - a_{22}\alpha_{12}) \theta_{1}$$

$$+ (-a_{12}\alpha_{12} - a_{22}\alpha_{22} - 2K_{2}) \theta_{2}$$

$$+ (-a_{12}\alpha_{13} - a_{22}\alpha_{23}) \theta_{d}$$

$$+ (-a_{12}\alpha_{14} - a_{22}\alpha_{24}) \theta_{L1}$$

From the above four equations (4-40), (4-41), (4-42) and (4-43) equating both sides of $d\lambda_1/dt$ and $d\lambda_2/dt$; the coefficients of θ_1 , θ_2 , θ_d , θ_{L1} and θ_{L2} are identical. Thus:

(4-43)

+ (- a₁₂a₁₅ - a₂₂a₂₅) e₁₂

$$(a_{11}\alpha_{11} + a_{21}\alpha_{12} - \frac{b^2}{2}\alpha_{12}^2) = (-a_{11}\alpha_{11} - a_{21}\alpha_{12} - 2K_1)$$
 (4-44)

$$(a_{12}\alpha_{11} + a_{22}\alpha_{12} - \frac{b^2}{2}\alpha_{12}\alpha_{22}) = (-a_{11}\alpha_{12} - a_{21}\alpha_{22})$$
 (4-45)

$$\left(-\frac{b^{2}}{2}\alpha_{12}\alpha_{23}\right) = \left(-\alpha_{11}\alpha_{13} - \alpha_{21}\alpha_{23} + 2K_{1}\right) \tag{4-46}$$

$$(d_{22}\alpha_{12} - \frac{b^2}{2}\alpha_{12}\alpha_{25}) = (-a_{11}\alpha_{15} - a_{21}\alpha_{25})$$
 (4-48)

$$(a_{11}\alpha_{12} + a_{21}\alpha_{22} - \frac{b^2}{2}\alpha_{12}\alpha_{22}) = (-a_{12}\alpha_{11} - a_{22}\alpha_{12})$$
 (4-49)

$$(a_{12}a_{12} + a_{22}a_{22} - \frac{b^2}{2}a_{22}^2) = (-a_{12}a_{12} - a_{22}a_{22} - 2K_2)$$
 (4-50)

$$\left(-\frac{b^{2}}{2}\alpha_{22}\alpha_{23}\right) = \left(-\alpha_{12}\alpha_{13} - \alpha_{22}\alpha_{23}\right) \tag{4-51}$$

$$\left(d_{11}a_{12} - \frac{b^2}{2}a_{22}a_{24}\right) = \left(-a_{12}a_{14} - a_{22}a_{24}\right) \tag{4-52}$$

$$(d_{22}\alpha_{22} - \frac{b^2}{2}\alpha_{22}\alpha_{25}) = (-a_{12}\alpha_{15} - a_{22}\alpha_{25})$$
 (4-53)

In the above ten equations, equation (4-45) is identical to equation (4-49), and rearranging all of the nine independent equations gives:

$$K_1 + a_{11}\alpha_{11} + a_{21}\alpha_{12} - \frac{b^2}{4} \alpha_{12}^2 = 0$$
 (4-54)

$$a_{12}\alpha_{11} + (a_{11} + a_{22})\alpha_{12} + a_{21}\alpha_{22} - \frac{b^2}{2}\alpha_{12}\alpha_{22} = 0$$
 (4-55)

$$-2K_1 + a_{11}\alpha_{13} + a_{21}\alpha_{23} - \frac{b^2}{2}\alpha_{12}\alpha_{23} = 0 (4-56)$$

$$d_{11}d_{11} + a_{11}d_{14} + a_{21}d_{24} - \frac{b^2}{2}d_{12}d_{24} = 0 (4-57)$$

$$d_{22}\alpha_{12} + a_{11}\alpha_{15} * a_{21}\alpha_{25} - \frac{b^2}{2}\alpha_{12}\alpha_{25} = 0 (4-58)$$

$$K_2 + a_{12}\alpha_{12} + a_{22}\alpha_{22} - \frac{b^2}{4}\alpha_{22}^2 = 0$$
 (4-59)

$$a_{12}a_{13} + a_{22}a_{23} - \frac{b^2}{2}a_{22}a_{23}$$
 = 0 (4-60)

$$d_{11}\alpha_{12} + a_{12}\alpha_{14} + a_{22}\alpha_{24} - \frac{b^2}{2}\alpha_{22}\alpha_{24} = 0 (4-61)$$

$$a_{12}a_{15} + d_{22}a_{22} + a_{22}a_{25} - \frac{b^2}{2}a_{22}a_{25} = 0$$
 (4-62)

From the above nine non-linear algebraic equations nine unknown coefficients can be solved by a Newton-Raphson iteration method using a digital computer (See Appendix 1).

CHAPTER

MATHEMATICAL DERIVATION OF THE OAC SCHEME FOR A CONTINUOUS STIRRED TANK REACTOR

5.1. Optimal adaptive control (OAC) system

Rewriting the linearised process equations gives :

$$\frac{d\theta_1}{dt} = a_{11}\theta_1 + a_{12}\theta_2 + d_{11}\theta_{L1} = f_1 (\theta_1, \theta_2, \theta_{L1})$$
 (5-1)

$$\frac{d\theta_{2}}{dt} = a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2} + bU = f_{2}(\theta_{1}, \theta_{2}, \theta_{L2}, U)$$
 (5-2)

$$U = \Delta Q = Q_{c} - Q_{cs}$$
 (5-3)

with the initial and final conditions

$$\theta_1(t_0) = \theta_{10}$$
 (5-4-1)

$$\theta_2(t_0) = \theta_{20}$$
 (5-4-2)
 $\theta_1(t_0) = \theta_{10}$ (5-5-1)

$$\theta_{1}(t_{f}) = \theta_{1f} \tag{5-5-1}$$

$$\theta_{2}(t_{f}) = \theta_{2f} \tag{5-5-2}$$

The system is operated and controlled to follow the input response of the optimal concentration profile generated from the OMR scheme, $\theta_1^r(t)$ and forced to the final steady state in the presence of unmeasurable changed parameters or laod variables.

The proposed performance index is as follows:

$$J(U) = \int_{t_0}^{t_f} \left[K_3 (\theta_1^r - \theta_1)^2 + U^2 \right] dt$$
 (5-6)

where: $\theta_1^r(t) = \theta_1^*(t) = the optimal concentration profile generated$ from the OMR scheme

K = weighting factor.

Define the functional equation as:

$$f(\theta_1, \theta_1^r) = Min \int_{t_0}^{t_1} \left[K_3 (\theta_1^r - \theta_1)^2 + U^2 \right] dt$$
 (5-7)

or

$$f(\theta_1, \theta_1^r) = \int_{t_0}^{t_f} \left[K_3 (\theta_1^r - \theta_1)^2 + U^{*2} \right] dt$$
 (5-8)

Equation (5-8) states that the minimum performance index is a function of θ_1 and θ_1^r , subject to the process equations (5-1) and (5-2) with boundary conditions (5-4) and (5-5) and generated by the optimal control law U*(t), in the presence of unmeasurable changed parameters or load variables. Here the constraints within U*(t) will be considered with the same conditions as discussed in (4.4)

Using the maximum principle, let the new variable $\theta_3(t)$ be introduced as performance index:

$$\theta_3(t) = \int_{t_0}^{t} \left[K_3 (\theta_1^r - \theta_1)^2 + U^2 \right] dt$$
 (5-9)

or
$$\frac{d\theta_3}{dt} = K_3(\theta_1^r - \theta_1)^2 + U^2 = f_3(\theta_1, \theta_1^r, U)$$
 (5-10)

Then the original performance index becomes:

$$S(t_f) = C_3 \theta_3(t_f) \qquad (5-11)$$

where

$$S(t_f) = performance index$$
 $c_3 = \lambda_3(t_f) = 1$

From the maximum principle a Hamiltonian equation is introduced as follows:

$$H (\theta_{1}, \theta_{2}, U, \lambda) = \sum_{i=1}^{3} \lambda_{i}^{f}_{i}$$

$$= \lambda_{1} \left[a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1} \right]$$

$$+ \lambda_{2} \left[a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L1} + bU \right]$$

$$+ \lambda_{3} \left[K_{3} (\theta_{1}^{r} - \theta_{1})^{2} + U^{2} \right]$$
(5-12)

where λ_1, λ_2 and λ_3 are adjoint variables, and are subject to the following equations:

$$\frac{\mathrm{d}\lambda_{i}}{\mathrm{d}t} = -\left(\frac{\partial H}{\partial \Theta_{i}}\right)$$

or

$$\frac{d\lambda_1}{dt} = -\frac{\partial H}{\partial \theta_1} = -a_{11}\lambda_1 - a_{21}\lambda_2 + 2K_3 (\theta_1^r - \theta_1)\lambda_3 \qquad (5-13)$$

$$\frac{d\lambda_2}{dt} = -\frac{\partial H}{\partial \theta_2} = -a_{12}\lambda_1 - a_{22}\lambda_2$$
 (5-14)

$$\frac{d\lambda_3}{dt} = -\frac{\partial H}{\partial \theta_3} = 0 ag{5-15}$$

$$\frac{d\lambda_{3}}{dt} = 0 \; ; \; \lambda_{3}(t_{f}) = 1 \quad ... \quad \lambda_{3}(t) = 1 \qquad (5-16)$$

Substituting $\lambda_3(t)$ into equations (5-12) and (5-13), and rewriting equation (5-4):

$$H (\theta_{1}, \theta_{2}, U, \lambda) = \begin{bmatrix} a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1} \end{bmatrix} \lambda_{1}$$

$$+ \begin{bmatrix} a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2} + bU \end{bmatrix} \lambda_{2}$$

$$+ \begin{bmatrix} K_{3} (\theta_{1}^{r} - \theta_{1})^{2} + U^{2} \end{bmatrix}$$
 (5-17)

$$\frac{d\lambda_1}{dt} = -a_{11}\lambda_1 - a_{21}\lambda_2 + 2K_3 (\theta_1^r - \theta_1)$$
 (5-18)

$$\frac{d\lambda_2}{dt} = -a_{12}\lambda_1 - a_{22}\lambda_2$$
 (5-14)

The optimal control law will be determined from the condition that:

$$\frac{1}{9} = 0$$

or $b\lambda_2 + 2U = 0$

...
$$U^*(t) = -(\frac{b}{2}) \lambda_2(t)$$
 (5-19)

Since the system will be forced to operate around the steady state under fixed boundary conditions, the boundary value of $\lambda_1(t)$ and $\lambda_2(t)$ will be free:

Initial conditions:

$$\lambda_1(t_0) = \text{free} \tag{5-20-1}$$

$$\lambda_2(t_0) = \text{free} \tag{5-20-2}$$

Final conditions:

$$\lambda_{1}(t_{f}) = free \qquad (5-21-1)$$

$$\lambda_2(t_f) = free (5-21-2)$$

Since the above free boundary conditions are for both $\lambda_1(t)$ and $\lambda_2(t)$, they can be set to be any function between the time $t_0 \leqslant t \leqslant t_f$, and subject to the equations (5-1), (5-2), (5-18), (5-14) and (5-19).

By using the same general drived principles and techniques described in Chapters 3 and 4, the more complicated optimal PID

of the OAC scheme and the corresponding coefficients will be determined in the following sections.

5.2. Optimal P of OAC scheme

Let

$$\lambda_{1}(t) = \beta_{11}\theta_{1}(t) + \beta_{12}\theta_{2}(t) + \beta_{13}\theta_{1}^{r}(t) + \beta_{14}\theta_{L1}(t) + \beta_{15}\theta_{L2}(t)$$

$$(5-22)$$

$$\lambda_{2}(t) = \beta_{12}\theta_{1}(t) + \beta_{22}\theta_{2}(t) + \beta_{23}\theta_{1}^{r}(t) + \beta_{24}\theta_{L1}(t) + \beta_{25}\theta_{L2}(t)$$

(5-23)

where:

$$\theta_1(t)$$
, $\theta_2(t)$, θ_1^r (t), $\theta_{L1}(t)$, and $\theta_{L2}(t)$

are state variables, model reference input variable, and load variables respectively and can be measurable and β_{11} , β_{12} , β_{13} , β_{14} , β_{15} , β_{22} , β_{23} , β_{24} and β_{25} are coefficients to be determined.

After all necessary coefficients have been determined, substituting $\lambda_2(t)$ of equation (5-23) into equation (5-19), then the optimal control law will be:

$$U^{*}(t) = -\frac{b}{2} \beta_{12} \theta_{1}(t) + \beta_{22} \theta_{2}(t) + \beta_{23} \theta_{1}^{r}(t) + \beta_{24} \theta_{L1}(t) + \beta_{25} \theta_{L2}(t)$$

$$(5-24)$$

when
$$\Theta_1(t) = \Theta_1^r(t)$$
; $t_0 \le t \le t_f$

then the response of the OAC scheme is the same as the OMR scheme, since both schemes contain the same process and boundary conditions and both optimal control laws are also the same. Thus:

$$\begin{bmatrix} U^{*}(t) \end{bmatrix}_{\theta_{1}} = \theta_{1}^{r}$$

$$= -\frac{b}{2} \begin{bmatrix} (\beta_{12} + \beta_{23}) \theta_{1}^{r}(t) + \beta_{22} \theta_{2}(t) + \beta_{24} \theta_{L1}(t) \\ + \beta_{25} \theta_{L2}(t) \end{bmatrix}$$

$$(5-25)$$

or

$$m^{*}(t) + \frac{b}{2} (\beta_{12} + \beta_{23}) \theta_{1}^{r}(t)$$

$$= -\frac{b}{2} \left[\beta_{22} \theta_{2}(t) + \beta_{24} \theta_{L1}(t) + \beta_{25} \theta_{L2}(t) \right]$$
 (5-26)

Substituting equation (5-26) into equation (5-24), simplifying and applying the perturbation principle shown in Optimal P of the OAC scheme in (3.4.1.) (Chapter 3), leads to:

$$U^*(t) = m^*(t) + \frac{b}{2} \beta_{12} \left[\theta_1^r(t) - \theta_1(t) \right]$$
where
$$\beta_{12} = \beta_{12}(C, K, P^*)$$

$$= \text{ optimal P coefficient}}$$

$$C = \text{ all process constants}$$

$$K = \text{ all wwighting factors}$$

$$P^* = \text{ all process parameters with}$$

$$\text{normal value}$$

Equation (5-27) states that: the optimal control law of the OAC scheme is proportional to the perturbation of the Optimal control law from the OMR scheme and the corresponding coefficient \mathfrak{g}_{12} will be determined with constant normal parameters.

Comparing equation (5-27) with equation (3-35) in Chapter 3 (3.4.1.), shows that equation (5-27) is a special case of equation (3-35), the general optimal P of the OAC scheme.

5.3. Determination of Optimal P coefficient, \$ 12.

Differentiating equations (5-22) and (5-23), neglecting the derivatives of θ_1^r , θ_{L1} and θ_{L2} and substituting equations (5-1), (5-2) and (5-24) into the differentiated equations, gives:

$$\frac{d\lambda_{1}}{dt} = \beta_{11}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) + \beta_{12} \left[a_{21}\theta_{1} + a_{22}\theta_{2} \right]
d_{22}\theta_{L2} - \frac{b^{2}}{2}(\beta_{12}\theta_{1} + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2}) \right]
= (a_{11}\beta_{11} + a_{21}\beta_{12} - \frac{b^{2}}{2}\beta_{12}) \theta_{1}
+ (a_{12}\beta_{11} + a_{22}\beta_{12} - \frac{b^{2}}{2}\beta_{12}\beta_{22}) \theta_{2}
- (\frac{b^{2}}{2}\beta_{12}\beta_{23}) \theta_{1}^{r} + d_{11}\beta_{11} - \frac{b^{2}}{2}\beta_{12}\beta_{24}) \theta_{L1}
+ (d_{22}\beta_{12} - \frac{b^{2}}{2}\beta_{12}\beta_{25}) \theta_{L2}$$
(5-28)
$$\frac{d\lambda_{2}}{dt} = \beta_{12}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) + \beta_{22} \left[a_{21}\theta_{1} + a_{22}\theta_{2} \right]
+ d_{22}\theta_{L2} - \frac{b^{2}}{2}(\beta_{12}\theta_{1} + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2}) \right]
= (a_{11}\theta_{12} + a_{21}\theta_{22} - \frac{b^{2}}{2}\beta_{12}\beta_{22}) 1
+ (a_{12}\beta_{12} + a_{22}\beta_{22} - \frac{b^{2}}{2}\beta_{22}) 2
- (\frac{b^{2}}{2}\beta_{22}\beta_{23}) \theta_{1}^{r} + (d_{11}\beta_{12} - \frac{b^{2}}{2}\beta_{22}\beta_{24}) \theta_{L1}
+ (d_{22}\theta_{22} - \frac{b^{2}}{2}\beta_{22}\beta_{25}) \theta_{L2}$$
(5-29)

Substituting equations (5-22) and (5-23) into equations (5-18) and (5-14), gives:

$$\frac{d\lambda_{1}}{dt} = -a_{11} (\beta_{11}\theta_{1} + \beta_{12}\theta_{2} + \beta_{13}\theta_{1}^{r} + \beta_{14}\theta_{L1} + \beta_{15}\theta_{L2})$$

$$-a_{21} (\beta_{12}\theta_{1} + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2})$$

$$+ 2K_{3} (\theta_{1}^{r} - \theta_{1})$$

$$= (-a_{11}\beta_{11} - a_{21}\beta_{12} - 2K_{3}) \theta_{1}$$

$$+ (-a_{11}\beta_{12} - a_{21}\beta_{22}) \theta_{2}$$

$$+ (-a_{11}\beta_{13} - a_{21}\beta_{23} + 2K_{3}) \theta_{1}^{r}$$

$$+ (-a_{11}\beta_{14} - a_{21}\beta_{24}) \theta_{L1}$$

$$+ (-a_{11}\beta_{15} - a_{21}\beta_{25}) \theta_{L2}$$
(5-30)

$$\frac{d\lambda_{2}}{dt} = -a_{12} (\beta_{11}e_{1} + \beta_{12}e_{2} + \beta_{13}e_{1}^{r} + \beta_{14}e_{L1} + \beta_{15}e_{L2})$$

$$-a_{22} (\beta_{12}e_{1} + \beta_{22}e_{2} + \beta_{23}e_{1}^{r} + \beta_{24}e_{L1} + \beta_{25}e_{L2})$$

$$= (-a_{12}\beta_{11} - a_{22}\beta_{12}) e_{1}$$

$$+ (-a_{12}\beta_{12} - a_{22}\beta_{22}) e_{2}$$

$$+ (-a_{12}\beta_{13} - a_{22}\beta_{23}) e_{1}^{r}$$

$$+ (-a_{12}\beta_{14} - a_{22}\beta_{24}) e_{L1}$$

$$+ (-a_{12}\beta_{15} - a_{22}\beta_{25}) e_{L2}$$
(5-31)

From the above four equations (5-28), (5-29), (5-30) and (5-31), equating both sides of $\frac{d\lambda_1}{dt}$ and $\frac{d\lambda_2}{dt}$, the coefficients of θ_1 , θ_2 , θ_1^r , θ_{L1} and θ_{L2} are identical. Thus:

$$(a_{11}B_{11} + a_{21}B_{12} - \frac{b^2}{2}B_{12}^2) = (-a_{11}B_{11} - a_{21}B_{12} - 2K_3)$$
 (5-32)

$$(a_{12}\beta_{11} + a_{22}\beta_{12} - \frac{b^2}{2}\beta_{12}\beta_{22}) = (-a_{11}\beta_{12} - a_{21}\beta_{22})$$
 (5-33)

$$\left(-\frac{b^{2}}{2}\beta_{12}\beta_{23}\right) = \left(-a_{11}\beta_{13} - a_{21}\beta_{23} + 2K_{3}\right) \tag{5-34}$$

$$\left(d_{11}\beta_{11} - \frac{b^2}{2}\beta_{12}\beta_{24}\right) = \left(-a_{11}\beta_{14} - a_{21}\beta_{24}\right) \tag{5-35}$$

$$(d_{22}\beta_{12} - \frac{b^2}{2}\beta_{12}\beta_{25}) = (-a_{11}\beta_{15} - a_{21}\beta_{25})$$
 (5-36)

$$(a_{11}\beta_{12} + a_{21}\beta_{22} - \frac{b^2}{2}\beta_{12}\beta_{22}) = (-a_{12}\beta_{11} - a_{22}\beta_{12})$$
 (5-37)

$$(a_{12}\beta_{12} + a_{22}\beta_{22} - \frac{b^2}{2}\beta_{22}) = (-a_{12}\beta_{12} - a_{22}\beta_{22})$$
 (5-38)

$$\left(-\frac{b^2}{2}\beta_{22}\beta_{23}\right) = \left(-a_{12}\beta_{13} - a_{22}\beta_{23}\right) \tag{5-39}$$

$$(a_{11}\beta_{12} - \frac{b^2}{2}\beta_{22}\beta_{22}) = (-a_{12}\beta_{14} - a_{22}\beta_{24})$$
 (5-40)

$$(a_{22}n_{22} - \frac{b^2}{2}n_{22}n_{25}) = (-a_{12}n_{15} - a_{22}n_{25})$$
 (5-41)

In the above ten equations, equation (5-33) is identical to equation (5-37). Rearrangement of the remaining nine independent equations yields:

$$K_3 + a_{11}\beta_{11} + a_{21}\beta_{12} - \frac{b^2}{4}\beta_{12}^2 = 0$$
 (5-42)

$$a_{12}\beta_{11} + (a_{11} + a_{22})\beta_{12} + a_{21}\beta_{22} - \frac{b^2}{2}\beta_{12}\beta_{22} = 0$$
 (5-43)

$$-2K_3 + a_{11}B_{13} + a_{21}B_{23} - \frac{b^2}{2}B_{12}B_{23} = 0 (5-44)$$

$$a_{11}\beta_{11} + a_{11}\beta_{14} + a_{21}\beta_{24} - \frac{b^2}{2}\beta_{12}\beta_{24} = 0 \quad (5-45)$$

$$d_{22}\beta_{12} + a_{11}\beta_{15} + a_{21}\beta_{25} - \frac{b^2}{2}\beta_{12}\beta_{25} = 0 (5-46)$$

$$d_{12}\beta_{12} + a_{22}\beta_{22} - \frac{b^2}{4}\beta_{22}^2 = 0 (5-47)$$

$$a_{12}\beta_{13} + a_{22}\beta_{23} - \frac{b^2}{2}\beta_{22}\beta_{23}$$
 = 0 (5-48)

$$d_{11}\beta_{12} + a_{12}\beta_{14} + a_{22}\beta_{24} - \frac{b^2}{2}\beta_{22}\beta_{24} = 0 (5-49)$$

$$d_{22}\beta_{22} + a_{12}\beta_{15} + a_{22}\beta_{25} - \frac{b^2}{2}\beta_{22}\beta_{25} = 0 \quad (5-50)$$

From the above nine non-linear algebraic equations nine unknown coefficients can be solved. Equations (5-42) to (5-50) are in the same form as equations (4-54) to (4-62) of the OMR scheme, because both schemes are derived with the same optimal proportional control action. Solving equations (5-42), (5-43) and (5-47), the coefficient β_{12} will be determined by a Newton-Raphson iteration method using a digital computer (see Appendix 1).

5.4. Optimal P + I of OAC scheme

Let:

$$\lambda_{1} = \beta_{11}\theta_{1} + \beta_{12}\theta_{2} + \beta_{13}\theta_{1}^{r} + \beta_{14}\theta_{L1} + \beta_{15}\theta_{L2}$$

$$+ \beta_{16} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt + \epsilon_{1} \int_{t_{0}}^{t} \left[\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \right] dt + \cdots$$
(5-51)

$$\lambda_{2} = \beta_{21}\theta_{1} + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L1}$$

$$+ \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt + \epsilon_{2} \int_{t_{0}}^{t} \left[\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \right] dt + \dots$$
(5-52)

In the process control field, the integral control action is only represented by the single integration of the error variables and any double or higher integration is never used. This is because the use of integral control can eliminate offset, but it can also easily introduce unstable tendencies into the system if a large coefficient is selected; this is because the output of the integral controller always increases when the error is present. So in general it is not necessary to use double or higher integration in integral control. But actually in the broad physical sense, the double and higher integration of error variable must exist and is presented in equations (5-51) and (5-52).

Also in the derivation of Optimal P + I the single integration form is of interest and the double and higher integrals were neglected. Equation (5-51) and (5-52) then become:

$$\lambda_{1} = \beta_{11}\theta_{1} + \beta_{12}\theta_{2} + \beta_{13}\theta_{1}^{r} + \beta_{14}\theta_{L1} + \beta_{15}\theta_{L2}$$

$$+ \beta_{16} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \qquad (5-53)$$

$$\lambda_{2} = \beta_{21}\theta_{1} + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2}$$

$$+ \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \qquad (5-54)$$

where:

But in later derived procedures (see next section) for the first order derivatives of λ_1 and λ_2 , i.e. $\dot{\lambda}_1$ and $\dot{\lambda}_2$ from

equations (5-53) and (5-54), the integral form is automatically lost, and the coefficients \mathfrak{g}_{16} and \mathfrak{g}_{26} are always equal to zero (see next section's discussion). Hence the suggested strategy for derivation of Optimal P + I is that when λ_1 and λ_2 occur and the single integral form is to be retained, then the double integration should be introduced with the selection of comparatively small weighting factors ϵ_1 and ϵ_2 (see section 5)

After all the necessary coefficients have been determined, substituting $\lambda_2(t)$ of equation (5-54) into equation (5-19), then the optimal control law will be:

$$U^{*}(t) = -\frac{b}{2} \left[\beta_{21} \theta_{1} + \beta_{22} \theta_{2} + \beta_{23} \theta_{1}^{r} + \beta_{24} \theta_{L1} + \beta_{25} \theta_{L2} + \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \right]$$
(5-55)

when $\theta_{1}(t) = \theta_{1}(t)$; $t_{0} \le t \le t_{f}$

or:

$$m^{*}(t) + \frac{b}{2} (\beta_{21} + \beta_{23}) \theta_{1}^{r}$$

$$= -\frac{b}{2} (\beta_{22} \theta_{2} + \beta_{24} \theta_{L1} + \beta_{25} \theta_{L2}) \qquad (5-57)$$

Substituting equation (5-57) into equation (5-55) and simplifying and applying the perturbation principle shown in Optimal P + I of the OAC scheme in (3.4.2) leads to:

$$U^{*}(t) = m^{*}(t) + \frac{b}{2} \left\{ \beta_{21} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] + \beta_{26} \int_{t_{0}}^{t} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] dt \right\}$$

where: β_{21} ; $\beta_{26} = \beta_{21}(C,K,P^*)$; $\beta_{26}(C,K,P^*)$

= Optimal P + I coefficients

(5-58)

C = process constants

K = weighting factors

P* = process parameters with normal

value

Equation (5-58) states that: the optimal control law of the OAC scheme is proportional to the perturbation and the integral of perturbation of the optimal control law from the OMR scheme and the corresponding coefficients \$ 21 and \$ 26 will be determined with normal parameters.

Comparing equation (5-58) with equation (3-44) in Chapter 3 (3.4.2), shows that equation (5-58) is a special case of equation (3-44) the general Optimal P + I of the OAC scheme.

Differentiation of equations (5-51) and (5-52) and neglecting the derivatives of $\mathbf{e}_{1}^{\mathbf{r}}$, \mathbf{e}_{L1} and \mathbf{e}_{L2} :

$$\frac{d\lambda_1}{dt} = \beta_{11} \frac{d\theta_1}{dt} + \beta_{12} \frac{d\theta_2}{dt} + \beta_{16}(\theta_1 - \theta_1^r) + \epsilon_1 \int_{t_0}^{t} (\theta_1 - \theta_1^r) dt$$
(5-59)

$$\frac{d\lambda_2}{dt} = B_{21} \frac{d\theta_1}{dt} + B_{22} \frac{d\theta_2}{dt} + B_{26}(\theta_1 - \theta_1^r) + \epsilon_2 \int_{t_0}^{t} (\theta_1 - \theta_1^r) dt$$
 (5-60)

Substituting equations (5-1), (5-2) and (5-55) into equations (5-59) and (5-60) yields:

$$\frac{d\lambda_{1}}{dt} = \beta_{11}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1})$$

$$+ \beta_{12} a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2} - \frac{b^{2}}{2}(\beta_{21}\theta_{1} + \beta_{22}\theta_{2})$$

$$+ \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2} + \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$+ \beta_{16} (\theta_{1} - \theta_{1}^{r}) + \ell_{1} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$= (a_{11}\beta_{11} + a_{21}\beta_{12} + \beta_{16} - \frac{b^{2}}{2}\beta_{12}\beta_{21}) \theta_{1}$$

$$+ (a_{12}\beta_{11} + a_{22}\beta_{12} - \frac{b^{2}}{2}\beta_{12}\beta_{22}) \theta_{2}$$

$$- (\frac{b^{2}}{2}\beta_{12}\beta_{23} + \beta_{16}) \theta_{1}^{r}$$

$$+ (d_{11}\beta_{11} - \frac{b^{2}}{2}\beta_{12}\beta_{24}) \theta_{L1}$$

$$+ (d_{22}\theta_{12} - \frac{b^{2}}{2}\beta_{12}\beta_{25}) \theta_{L2}$$

$$= (\frac{b^{2}}{2}\beta_{12}\beta_{26} + \ell_{1}) \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \qquad (5-61)$$

$$\frac{d\lambda_{2}}{dt} = \beta_{21}(a_{11}e_{1} + a_{12}e_{2} + d_{11}e_{L1})$$

$$+ \beta_{22} \left[a_{21}e_{1} + a_{22}e_{2} + d_{22}e_{L2} - \frac{b^{2}}{2}(\beta_{21}e_{1} + \beta_{22}e_{2}) + \beta_{22}e_{2} + \beta_{22}e_{L2} - \frac{b^{2}}{2}(\beta_{21}e_{1} + \beta_{22}e_{2}) + \beta_{23}e_{1}^{r} + \beta_{24}e_{L1} + \beta_{25}e_{L2} + \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \right]$$

$$+ \beta_{23}e_{1}^{r} + \beta_{24}e_{L1} + \beta_{25}e_{L2} + \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$+ \beta_{26}(\theta_{1} - \theta_{1}^{r}) + \epsilon_{2} \int_{t_{0}}^{t_{1}} (\theta_{1} - \theta_{1}^{r}) dt$$

$$= (a_{11}\beta_{21} + a_{22}\beta_{22} - \frac{b^{2}}{2}\beta_{21}\beta_{22} + \beta_{26}) \theta_{1}$$

$$+ (a_{12}\beta_{21} + a_{22}\beta_{22} - \frac{b^{2}}{2}\beta_{22}) \theta_{2}$$

$$- (\frac{b^{2}}{2}\beta_{22}\beta_{23} + \beta_{26}) \theta_{1}^{r}$$

$$+ (d_{11}\beta_{21} - \frac{b^{2}}{2}\beta_{22}\beta_{26}) \theta_{L1}$$

$$+ (d_{22}\beta_{22} - \frac{b^{2}}{2}\beta_{22}\beta_{25}) \theta_{L2}$$

$$+ (-\frac{b^{2}}{2}\beta_{22}\beta_{26} + \epsilon_{2}) \int_{t}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$
(5-62)

Substituting equations (5-53) and (5-54) into equations (5-18) and (5-14) gives:

$$\frac{d\lambda_{1}}{dt} = a_{11}(R_{11}\theta_{1} + R_{12}\theta_{2} + R_{13}\theta_{1}^{r} + R_{14}\theta_{L1} + R_{15}\theta_{L2} + R_{16}\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$- a_{21}(R_{21}\theta_{1} + R_{22}\theta_{2} + R_{23}\theta_{1}^{r} + R_{24}\theta_{L1} + R_{25}\theta_{L2} + R_{26}\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$+ 2K_{3}(\theta_{1}^{r} - \theta_{1})$$

$$= (-a_{11}B_{11} - a_{21}B_{21} - 2K_{3})\theta_{1} + (-a_{11}B_{12} - a_{21}B_{22})\theta_{2}$$

$$+ (-a_{11}B_{13} - a_{21}B_{23} + 2K_{3})\theta_{1}^{r} + (-a_{11}B_{14} - a_{21}B_{24})\theta_{11}$$

$$+ (-a_{11}B_{15} - a_{21}B_{25})\theta_{12} + (-a_{11}B_{16} - a_{21}B_{26})\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$(5-63)$$

$$\frac{d\lambda_{2}}{dt} = -a_{12}(\beta_{11}\theta_{1} + \beta_{12}\theta_{2} + \beta_{13}\theta_{1}^{r} + \beta_{14}\theta_{L1} + \beta_{15}\theta_{L2} + \beta_{16}\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r})dt$$

$$-a_{22}(\beta_{21}\theta_{1} + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2} + \beta_{26}\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r})dt$$

$$= (-a_{12}\beta_{11} - a_{22}\beta_{21})\theta_{1} + (-a_{12}\beta_{12} - a_{22}\beta_{22})\theta_{2}$$

$$+ (-a_{12}\beta_{13} - a_{22}\beta_{23})\theta_{1}^{r} + (-a_{12}\beta_{14} - a_{22}\beta_{24})\theta_{L1}$$

$$+ (-a_{12}\beta_{15} - a_{22}\beta_{25})\theta_{L2} + (-a_{12}\beta_{16} - a_{22}\beta_{26})\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r})dt$$

$$+ (-a_{12}\beta_{15} - a_{22}\beta_{25})\theta_{L2} + (-a_{12}\beta_{16} - a_{22}\beta_{26})\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r})dt$$

$$+ (-a_{12}\beta_{15} - a_{22}\beta_{25})\theta_{L2} + (-a_{12}\beta_{16} - a_{22}\beta_{26})\int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r})dt$$

From the above four equations (5-61), (5-62), (5-63) and (5-64), equating both sides of $\frac{d\lambda_1}{dt}$ and $\frac{d\lambda_2}{dt}$ the coefficients of θ_1 , θ_2 , θ_1^r , θ_{L1} , θ_{L2} and θ_1^r and θ_2^r dt are indetical. Thus:

$$(a_{11}\beta_{11} + a_{21}\beta_{12} - \frac{b^2}{2}\beta_{12}\beta_{21} + \beta_{16}) = (-a_{11}\beta_{11} - a_{21}\beta_{21} - 2K_3)$$
(5-65)

$$(a_{12}\beta_{11} + a_{22}\beta_{12} - \frac{b^2}{2}\beta_{12}\beta_{22}) = (-a_{11}\beta_{12} - a_{21}\beta_{22})$$
 (5-66)

$$\left(-\frac{b^2}{2}\beta_{12}\beta_{22}-\beta_{16}\right) = \left(-a_{11}\beta_{13}-a_{21}\beta_{23}+2K_3\right) \tag{5-67}$$

$$(a_{11}B_{11} - \frac{b^2}{2}B_{12}B_{24}) = (-a_{11}B_{14} - a_{21}B_{24})$$
 (5-68)

$$(a_{22}n_{12} - \frac{b^2}{2}n_{12}n_{25}) = (-a_{11}n_{15} - a_{21}n_{25})$$
 (5-69)

$$(-\frac{b^2}{2} n_{12} n_{26} + e_1) = (-a_{11} n_{16} - a_{21} n_{26})$$
 (5-70)

$$(a_{11}B_{21} + a_{21}B_{22} - \frac{b^2}{2}B_{21}B_{22} + B_{26}) = (-a_{12}B_{11} - a_{22}B_{21})$$
 (5-71)

$$(a_{12}\beta_{21} + a_{21}\beta_{22} - \frac{b^2}{2}\beta_{22}) = (-a_{12}\beta_{12} - a_{22}\beta_{22})$$
 (5-72)

$$\left(-\frac{b^2}{2}\beta_{22}\beta_{23} - \beta_{26}\right) = \left(-a_{12}\beta_{13} - a_{22}\beta_{23}\right) \tag{5-73}$$

$$(d_{11}\beta_{21} - \frac{b^2}{2}\beta_{22}\beta_{24}) = (-a_{12}\beta_{14} - a_{22}\beta_{24})$$
 (5-74)

$$(d_{22}R_{22} - \frac{d^2}{2}R_{22}R_{25}) = (-a_{12}R_{15} - a_{22}R_{25})$$
 (5-75)

$$\left(-\frac{b^2}{2}\beta_{22}\beta_{26} + \epsilon_2\right) = \left(-\frac{a_{21}\beta_{16} - a_{22}\beta_{26}}{a_{26}}\right) \tag{5-76}$$

After rearrangement and simplification of the above twelve equations (5-65) to (5-76), the following set of equations is obtained:

$$2K_3 + 2a_{11}B_{11} + a_{21}B_{12} + a_{21}B_{21} - \frac{b^2}{2}B_{12}B_{21} + B_{16} = 0 \qquad (5-77)$$

$$a_{12}\beta_{11} + (a_{11} + a_{22})\beta_{12} + a_{21}\beta_{22} - \frac{b^2}{2}\beta_{12}\beta_{22} = 0$$
 (5-78)

$$-2K_3 + a_{11}B_{13} - B_{16} + a_{21}B_{23} - \frac{b^2}{2}B_{12}B_{23} = 0 (5-79)$$

$$d_{11}B_{11} + a_{11}B_{14} + a_{21}B_{24} - \frac{b^2}{2}B_{12}B_{24} = 0 (5-80)$$

$$d_{22}\beta_{12} + a_{11}\beta_{15} + a_{21}\beta_{25} - \frac{b^2}{2}\beta_{12}\beta_{25} = 0 (5-81)$$

$$a_{11}B_{16} + a_{21}B_{26} - \frac{b^2}{2}B_{12}B_{26} + \epsilon_1$$
 = 0 (5-82)

$$a_{12}n_{11} + (a_{11} + a_{22})n_{21} + a_{21}n_{22} - \frac{b^2}{2}n_{21}n_{22} + n_{26} = 0$$
 (5-83)

$$a_{12}s_{12} + a_{12}s_{21} + 2a_{22}s_{22} - \frac{b^2}{2}s_{22}^2 = 0$$
 (5-84)

$$a_{12}n_{13} + a_{22}n_{23} - n_{26} - \frac{b^2}{2}n_{22}n_{23} = 0$$
 (5-85)

$$a_{12}B_{14} + d_{11}B_{21} + a_{22}B_{24} - \frac{b^2}{2}B_{22}B_{24}$$
 = 0 (5-86)

$$a_{12}R_{15} + d_{22}R_{22} + a_{22}R_{25} - \frac{b^2}{2}R_{22}R_{25} = 0$$
 (5-87)

$$a_{12}n_{16} + a_{22}n_{26} - \frac{b^2}{2}n_{22}n_{26} + \epsilon_2$$
 = 0 (5-88)

For determination of B_{21} and B_{26} , equations (5-77), (5-78), (5-82), (5-83), (5-84) and (5-88) among the above twelve non-linear equations must be solved by a Newton-Raphson iteration method by digital computer (see Appendix 1).

Among the above derived twelve non-linear algebraic equations, equations (5-82) and (5-87) are the more important ones to determine the coefficients β_{16} and β_{26} of Optimal P + I OAC scheme, as discussed below:

Rewriting these two equations gives:

$$a_{11}\beta_{16} + a_{21}\beta_{26} - \frac{b^2}{2}\beta_{12}\beta_{26} + \epsilon_1 = 0$$
 (5-82)

$$a_{12}\beta_{16} + a_{22}\beta_{26} - \frac{b^2}{2}\beta_{22}\beta_{26} + \epsilon_2 = 0$$
 (5-88)

 ϵ_1 and ϵ_2 are comparatively small values relative to all of the other weighting factors. So let $\epsilon_1 = \epsilon_2 = \epsilon$, and assume the coefficients β_{12} and β_{22} have been determined from other equations. Then β_{12} and β_{22} are determined coefficients (or

constants) in these two equations, and thus equations (5-82) and (5-88) become:

$$a_{11}B_{16} + a_{21}B_{26} - (\frac{b^2}{2}B_{12})B_{26} + \epsilon = 0$$
 (5-89)

$$a_{12}n_{16} + a_{22}n_{26} - (\frac{b^2}{2}n_{22})n_{26} + \epsilon = 0$$
 (5-90)

Solving for \$326 gives :

$$\beta_{26} = \frac{(a_{12} - a_{11})}{(a_{11}a_{22} - a_{12}a_{21}) - \frac{b^2}{2}(a_{11}\beta_{22} - a_{12}\beta_{12})}$$
 (5-91)

Equation (5-91) shows clearly that:

- (1) Equation (5-91) is a simple linear algebraic equation with constant slope which passes through zero when $\boldsymbol{\epsilon} = 0$.
- (2) For a given set of process constants and parameters, the slope of equation (5-91) must be constant
- (3) β_{26} must be equal to zero when ϵ is equal to zero.

 This is the condition of general single integral control (see equation (5-51) and (5-52)).
- (4) Since t is a small weighting factor which can arbitrarily start from a zero value, the condition for the general type of single integral control is the special case of the derived Optimal P + I system

5.6. Optimal P + I + D of OAC scheme

Let:

$$\lambda_{1} = R_{11}\theta_{1} + R_{12}\theta_{2} + R_{13}\theta_{1}^{r} + R_{14}\theta_{L1} + R_{15}\theta_{L2}$$

$$+ \left[R_{16} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt + \epsilon_{1} \int_{t_{0}}^{t} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt dt \right] + R_{17} \frac{d}{dt} (\theta_{1} - \theta_{1}^{r})$$
(5-92)

and

$$\lambda_2 = B_{21}\theta_1 + B_{22}\theta_2 + B_{23}\theta_3 + B_{24}\theta_{L1} + B_{25}\theta_{L2}$$

$$+ B_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt + \epsilon_{2} \int_{t_{0}}^{t} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt dt + B_{27} \frac{d}{dt} (\theta_{1} - \theta_{1}^{r})$$
(5-93)

When the double integral are neglected, equations (5-92) and (5-93) become:

$$\lambda_{1} = \beta_{11}\theta_{1} + \beta_{12}\theta_{2} + \beta_{13}\theta_{1}^{r} + \beta_{14}\theta_{L1} + \beta_{15}\theta_{L2} + \beta_{16} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt + \beta_{17} \frac{d}{dt} (\theta_{1} - \theta_{1}^{r}) dt$$
(5-94)

and

$$\lambda_{2} * \beta_{21} e_{1} + \beta_{22} e_{2} + \beta_{23} e_{1}^{r} + \beta_{24} e_{1L} + \beta_{25} e_{L2} + \beta_{26} \int_{t_{0}}^{t} (e_{1} - e_{1}^{r}) dt + \beta_{27} \frac{d}{dt} (e_{1} - e_{1}^{r}) dt$$

$$(5-95)$$

where 3 = coefficient to be determined

$$i = 1, 2$$

The derivation of optimal integral control coefficients is suggested by the same strategy as before. After all necessary coefficients have been determined, substituting $\lambda_2(t)$ into equation (5.19), will then give the optimal law:

$$U^* = -\frac{b}{2} \left[\mathbf{a}_{21} \mathbf{e}_1 + \mathbf{a}_{22} \mathbf{e}_2 + \mathbf{a}_{23} \mathbf{e}_1^r + \mathbf{a}_{24} \mathbf{e}_{L1} + \mathbf{a}_{25} \mathbf{e}_{L2} \right]$$

$$+ \mathbf{a}_{26} \int_{t_0}^{t} (\mathbf{e}_1 - \mathbf{e}_1^r) dt + \mathbf{a}_{27} \frac{d}{dt} (\mathbf{e}_1 - \mathbf{e}_1^r)$$
(5-96)

When $\theta_1(t) = \theta_1^{\dot{r}}(t)$; $t_0 \le t \le t_f$

$$\begin{bmatrix} U^*(t) \end{bmatrix}_{\boldsymbol{\theta}_1 = \boldsymbol{\theta}_1^r} = m^*(t)$$
 (5-97)

Then:

$$m^*(t) = -\frac{b}{2} \left[(R_{21} + R_{23}) e_1^r + R_{22} e_2 + R_{24} e_{L1} + R_{25} e_{L2} \right]$$
(5-98)

or .

$$m^*(t) + \frac{b}{2} (R_{21} + R_{23}) \theta_1^r = -\frac{b}{2} (R_{22} \theta_2 + R_{24} \theta_{L1} + R_{25} \theta_{L2})$$
 (5-99)

Substituting equation (5-99) into equation (5-96), simplifying and applying the perturbation principle shown in Optimal P + I + D of the OAC scheme in (3.4.3) yields:

$$U^{*}(t) = m^{*}(t) + \frac{b}{2} \left\{ \beta_{21} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] + \beta_{26} \right\} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] dt + \beta_{27} \frac{d}{dt} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] \right\}$$

where:
$$\beta_{21}$$
, β_{26} , $\beta_{27} = \beta_{21}(C,K,P^*)$, $\beta_{26}(C,K,P^*)$, $\beta_{27}(C,K,P^*)$

= Optimal P + I + D Coefficients

C = Process constants

K = Weighting factors

P* = Process parameters with normal

value

Equation (5-100) states that: the optimal control law of the OAC scheme is proportional to the perturbation integral of the perturbation, and derivative of the perturbation of the optimal control law from the OMR scheme and the corresponding coefficients β_{21} , β_{26} and β_{27} will be determined with normal parameters.

Comparing equation (5-100) with equation (3-53) in Chapter 3 (3.4.3) shows that equation (5-100) is a special case of equation (3-53), the general Optimal P + I + D of the OAC scheme.

5.7. Determination of Optimal P + I + D coefficients B 21, B 26 and B 27

Differentiation of equations (5-92) and (5-93), neglecting the first derivatives of θ_{L1} , θ_{L2} and the second derivative of $(\theta_1 - \theta_1^r)$, gives:

$$\frac{dx_{1}}{dt} = B_{11} \frac{d\theta_{1}}{dt} + B_{12} \frac{d\theta_{2}}{dt} + B_{13} \frac{d\theta_{1}^{r}}{dt} + B_{16} (\theta_{1} - \theta_{1}^{r}) + \epsilon_{1} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$
(5-101)

$$\frac{d\lambda_{2}}{dt} = B_{21} \frac{d\theta_{1}}{dt} + B_{22} \frac{d\theta_{2}}{dt} + B_{23} \frac{d\theta_{1}^{r}}{dt} + B_{26}(\theta_{1} - \theta_{1}^{r}) + \epsilon_{2} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$
(5-102)

Substituting equations (5-1), (5-2), and (5-96) into (5-101) and (5-102) and letting

$$\frac{\mathrm{d}}{\mathrm{d}t} \left(\boldsymbol{\theta}_{1} - \boldsymbol{\theta}_{1}^{r} \right) = \frac{\mathrm{d}\boldsymbol{\theta}_{1}}{\mathrm{d}t} - \frac{\mathrm{d}\boldsymbol{\theta}_{1}^{r}}{\mathrm{d}t} \tag{5-103}$$

gives:

$$\frac{d\lambda_{1}}{dt} = \beta_{11}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1})$$

$$+ \beta_{12} \left[a_{21}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2} - \frac{b^{2}}{2} (\beta_{21}\theta_{1} + \beta_{22}\theta_{2}) + \beta_{22}\theta_{2} + \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2} + \beta_{26} \right]_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$

$$+ \beta_{27} (a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) - \beta_{27} \frac{d\theta_{1}^{r}}{dt})$$

$$+ \beta_{13} \frac{d\theta_{1}^{r}}{dt} + \beta_{16} (\theta_{1} - \theta_{1}^{r}) + \epsilon_{1} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \qquad (5-104)$$

After rearrangement and simplification, equation (5-104) becomes:

$$\frac{d\lambda_{1}}{dt} = (a_{11}R_{11} + a_{21}R_{12} - \frac{b^{2}}{2}R_{12}R_{21} - \frac{b^{2}}{2}a_{11}R_{12}R_{27} + R_{16}) \theta_{1}
+ (a_{12}R_{11} + a_{22}R_{12} - \frac{b^{2}}{2}R_{12}R_{22} - \frac{b^{2}}{2}a_{12}R_{12}R_{27}) \theta_{2}
+ (-\frac{b^{2}}{2}R_{12}R_{23} - R_{16}) \theta_{1}^{r}
+ (d_{11}R_{11} - \frac{b^{2}}{2}R_{12}R_{24} - \frac{b^{2}}{2}d_{11}R_{12}R_{27}) \theta_{11}
+ (d_{22}R_{12} - \frac{b^{2}}{2}R_{12}R_{25}) \theta_{12}
+ (-\frac{b^{2}}{2}R_{12}R_{26} + \epsilon_{1}) \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt
+ (\frac{b^{2}}{2}R_{12}R_{27} + R_{13}) \frac{d\theta_{1}^{r}}{dt}$$
(5-105)

Similarly:

becomes:

$$\frac{d\lambda_{2}}{dt} = \beta_{21}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1})
+ \beta_{22} \left[a_{11}\theta_{1} + a_{22}\theta_{2} + d_{22}\theta_{L2} - \frac{b^{2}}{2}(\beta_{21}\theta_{1} + \beta_{22}\theta_{2}) \right]
+ \beta_{23}\theta_{1}^{r} + \beta_{24}\theta_{L1} + \beta_{25}\theta_{L2} + \beta_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt
+ \beta_{27}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) - \beta_{27} \frac{d\theta_{1}^{r}}{dt}) \right]
+ \beta_{23}\frac{d\theta_{1}^{r}}{dt} + \beta_{26}(\theta_{1} - \theta_{1}^{r}) + \epsilon_{2} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt$$
(5-106)

After rearrangement and simplification, equation (5-106)

$$\frac{d\lambda_{2}}{dt} = a_{11}B_{21} + a_{21}B_{22} - \frac{b^{2}}{2}B_{21}B_{22} - \frac{b^{2}}{2}a_{11}B_{22}B_{27} + B_{26}) \theta_{1}
+ (a_{12}B_{21} + a_{22}B_{22} - \frac{b^{2}}{2}a_{12}B_{22}B_{27}) \theta_{2}
+ (-\frac{b^{2}}{2}B_{22}B_{23} - B_{26}) \theta_{1}^{r}
+ (d_{11}B_{21} - \frac{b^{2}}{2}B_{22}B_{24} - \frac{b^{2}}{2}d_{11}B_{22}B_{27}) \theta_{L1}
+ (d_{22}B_{22} - \frac{b^{2}}{2}B_{22}B_{25}) \theta_{L2}
+ (-\frac{b^{2}}{2}B_{22}B_{26} + \epsilon_{2}) \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt
+ (\frac{b^{2}}{2}B_{22}B_{27} + B_{23}) \frac{d\theta_{1}^{r}}{dt}$$
(5-107)

Substituting equations (5-94) and (5-95) into equations (5-18) and (5-4) gives:

$$\frac{d\lambda_{1}}{dt} = -a_{11} \left[a_{11} e_{1} + a_{12} e_{2} + a_{12} e_{1}^{r} + a_{14} e_{11} + a_{15} e_{12} \right]
+ a_{16} \int_{t_{0}}^{t} (e_{1} - e_{1}^{r}) dt - a_{17} \frac{de_{1}^{r}}{dt} + a_{17} (a_{11} e_{1} + a_{12} e_{2})
+ a_{11} e_{11} \right] - a_{21} \left[a_{21} e_{1} + a_{22} e_{2} + a_{23} e_{1}^{r} \right]
+ a_{24} e_{11} + a_{25} e_{12} + a_{26} \int_{t_{0}}^{t} (e_{1} - e_{1}^{r}) dt - a_{27} \frac{de_{1}^{r}}{dt}
+ a_{27} (a_{11} e_{1} + a_{12} e_{2} + d_{11} e_{11}) \right] + 2 e_{3} (e_{1}^{r} - e_{1})
= (-a_{11} a_{11} - a_{21} a_{21} - 2 e_{3} - a_{11}^{2} a_{17} - a_{11}^{2} a_{21} a_{27}) e_{1}
+ (-a_{11} a_{12} - a_{21} a_{22} - a_{11}^{2} a_{12} a_{17} - a_{12}^{2} a_{11}^{2} a_{27}) e_{2}
+ (-a_{11} a_{15} - a_{21} a_{23} + 2 e_{3}^{2}) e_{12}
+ (-a_{11} a_{15} - a_{21} a_{25}) e_{12}
+ (-a_{11} a_{15} - a_{21} a_{25}) e_{12}
+ (-a_{11} a_{17} + a_{21} a_{25}) \frac{de_{1}^{r}}{dt} (e_{1} - e_{1}^{r}) dt
+ (a_{11} a_{17} + a_{21} a_{27}) \frac{de_{1}^{r}}{dt} (e_{1} - e_{1}^{r}) dt$$

$$(5-108)$$

$$\frac{d\lambda_{2}}{dt} = -a_{12} B_{11}\theta_{1} + B_{12}\theta_{2} + B_{13}\theta_{1}^{r} + B_{14}\theta_{L1} + B_{15}\theta_{L2} \\
+ B_{16} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt + B_{17}(a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) \\
- B_{17} \frac{d\theta_{1}^{r}}{dt} - a_{22} B_{21}\theta_{1} + B_{22}\theta_{2} + B_{23}\theta_{1}^{r} \\
+ B_{24}\theta_{L1} + B_{25}\theta_{L2} + B_{26} \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \\
+ B_{27} (a_{11}\theta_{1} + a_{12}\theta_{2} + d_{11}\theta_{L1}) - B_{27} \frac{d\theta_{1}^{r}}{dt} \\
= (-a_{12}B_{11} - a_{11}a_{12}B_{17} - a_{22}B_{21} - a_{11}a_{22}B_{27}) \theta_{1} \\
+ (-a_{12}B_{12} - a_{12}B_{17} - a_{22}B_{22} - a_{12}a_{22}B_{27}) \theta_{2} \\
+ (-a_{12}B_{13} - a_{22}B_{23}) \theta_{1}^{r} \\
+ (-a_{12}B_{14} - a_{12}A_{11}B_{17} - a_{22}B_{24} - a_{22}A_{11}B_{27}) \theta_{L1} \\
+ (-a_{12}B_{15} - a_{22}B_{25}) \theta_{L2} \\
+ (-a_{12}B_{16} - a_{22}B_{26}) \int_{t_{0}}^{t} (\theta_{1} - \theta_{1}^{r}) dt \\
+ (a_{12}B_{17} + a_{22}B_{27}) \frac{d\theta_{1}^{r}}{dt}$$
(5-109)

From the above four equations (5-105), (5-107), (5-108) and (5-109), equating both sides of $\frac{d\lambda_1}{dt}$ and $\frac{d\lambda_2}{dt}$, the coefficients of θ_1 , θ_2 , θ_1^r and θ_{L2} , θ_1^r and θ_{L2} , and θ_1^r are identical.

Thus:

$$a_{11}s_{11} + a_{21}s_{12} - \frac{b^2}{2}s_{12}s_{21} - \frac{b^2}{2}a_{11}s_{12}s_{27} + s_{16}$$

$$= -a_{11}s_{11} - a_{21}s_{21} - 2s_3 - a_{11}s_{17} - a_{11}a_{21}s_{27}$$
 (5-110)

$$a_{12}n_{11} + a_{22}n_{12} - \frac{b^2}{2}n_{12}n_{22} - \frac{b^2}{2} a_{12}n_{12}n_{27}$$

$$= -a_{11}B_{12} - a_{21}B_{22} - a_{11}a_{12}B_{17} - a_{12}a_{12}B_{27}$$
 (5-111)

$$-\frac{b^2}{2} \mathbf{a}_{12} \mathbf{a}_{23} - \mathbf{a}_{16} = -\mathbf{a}_{11} \mathbf{a}_{13} - \mathbf{a}_{21} \mathbf{a}_{23} + 2\mathbf{k}_3$$
 (5-112)

$$d_{11}\beta_{11} - \frac{b^2}{2}\beta_{12}\beta_{24} - \frac{b^2}{2}d_{11}\beta_{12}\beta_{27}$$

$$= -a_{11}\beta_{14} - a_{21}\beta_{24} - a_{11}d_{11}\beta_{17} - a_{21}d_{11}\beta_{27}$$
 (5-113)

$$a_{22}\beta_{12} - \frac{b^2}{2}\beta_{12}\beta_{25} = -a_{11}\beta_{15} - a_{21}\beta_{25}$$
 (5-114)

$$-\frac{b^2}{2}n_{12}n_{26} + \epsilon_1 = -a_{11}n_{16} - a_{21}n_{26}$$
 (5-115)

$$\frac{b^2}{2} \beta_{12} \beta_{27} + \beta_{13} = a_{11} \beta_{17} + a_{21} \beta_{27}$$
 (5-116)

$$a_{11}B_{21} + a_{21}B_{22} - \frac{b^2}{2}B_{21}B_{22} - \frac{b^2}{2}a_{11}B_{22}B_{27} + B_{26}$$

$$= -a_{12}B_{11} - a_{11}a_{12}B_{17} - a_{22}B_{21} - a_{11}a_{22}B_{27}$$
 (5-117)

$$a_{12}n_{21} + a_{22}n_{22} - \frac{b^2}{2}n_{22} - \frac{b^2}{2} a_{12}n_{22}n_{27}$$

$$= -a_{12}B_{12} - a_{12}^2B_{17} - a_{22}B_{22} - a_{12}a_{22}B_{27}$$
 (5-118)

$$-\frac{b^2}{2}R_{22}R_{23} - R_{26} = -a_{12}R_{13} - a_{22}R_{23}$$
 (5-119)

$$d_{11}n_{21} - \frac{b^2}{2}n_{22}n_{24} - \frac{b^2}{2}d_{11}n_{22}n_{27}$$

$$= -a_{12}\beta_{14} - a_{12}d_{11}\beta_{17} - a_{22}\beta_{24} - a_{22}d_{11}\beta_{27}$$
 (5-120)

$$d_{22}\beta_{22} - \frac{b^2}{2}\beta_{22}\beta_{25} = -a_{12}\beta_{15} - a_{22}\beta_{25}$$
 (5-121)

$$-\frac{b^2}{2}\beta_{22}\beta_{26} + \epsilon_2 = -a_{12}\beta_{16} - a_{22}\beta_{26}$$
 (5-122)

$$\frac{b^2}{2}\beta_{22}\beta_{27} + \beta_{23} = a_{12}\beta_{17} + a_{22}\beta_{27} \tag{5-123}$$

After rearrangement and simplification of the above fourteen equations (5-110) to (5-123), yields:

$$2K_{3} + 2 a_{11}R_{11} + a_{21}R_{12} + R_{16} + a_{11}R_{17} + a_{21}R_{21}$$
$$+ a_{11}a_{21}R_{27} - \frac{b^{2}}{2}R_{12}R_{21} - \frac{b^{2}}{2}a_{11}R_{12}R_{27} = 0$$
 (5-124)

$$+ a_{12}a_{21}a_{27} - \frac{b^2}{2}a_{12}a_{22} - \frac{b^2}{2}a_{12}a_{12}a_{27} = 0$$
 (5-125)

$$-2K_3 + a_{11}\beta_{13} - \beta_{16} + a_{21}\beta_{23} - \frac{b^2}{2}\beta_{12}\beta_{23} = 0 (5-126)$$

$$-\frac{b^2}{2}\beta_{12}\beta_{24} - \frac{b^2}{2}d_{11}\beta_{12}\beta_{27} = 0 (5-127)$$

$$a_{22}\beta_{12} + a_{11}\beta_{15} + a_{21}\beta_{25} - \frac{b^2}{2}\beta_{12}\beta_{25} = 0 \quad (5-128)$$

$$a_{11}^{0}_{16} + a_{21}^{0}_{26} - \frac{b^{2}}{2}^{0}_{12}^{0}_{26} + \epsilon_{1} = 0$$
 (5-129)

$$n_{13} - a_{11}n_{17} - a_{21}n_{27} + \frac{b^2}{2}n_{12}n_{27} = 0$$
 (5-130)

$$a_{12}B_{11} + a_{11}a_{12}B_{17} + (a_{11} + a_{22})B_{21} + a_{21}B_{22} + B_{26}$$

$$+ a_{11}a_{22}B_{27} - \frac{b^2}{2}B_{21}B_{22} - \frac{b^2}{2}a_{11}B_{22}B_{27} = 0 \quad (5-131)$$

$$a_{12}\beta_{12} + a_{12}^2\beta_{17} + a_{12}\beta_{21} + 2a_{22}\beta_{22} + a_{12}a_{22}\beta_{27}$$

$$-\frac{b^2}{2}\beta_{22}^2 - \frac{b^2}{2}a_{12}\beta_{22}\beta_{27} = 0 \quad (5-132)$$

$$a_{12}\beta_{13} + a_{22}\beta_{23} - \beta_{26} - \frac{b^2}{2}\beta_{22}\beta_{23} = 0$$
 (5-133)

$$-\frac{b^2}{2} \mathbf{a}_{22} \mathbf{a}_{24} - \frac{b^2}{2} \mathbf{a}_{11} \mathbf{a}_{22} \mathbf{a}_{27} = 0 (5-134)$$

$$a_{12}B_{15} + d_{22}B_{22} + a_{22}B_{25} - \frac{b^2}{2}B_{22}B_{25}$$
 = 0 (5-135)

$$a_{12}n_{16} + a_{22}n_{26} - \frac{b^2}{2}n_{22}n_{26} + \epsilon_2$$
 = 0 (5-136)

$$-a_{12}B_{17} - a_{22}B_{27} + B_{23} + \frac{b^2}{2}B_{22}B_{27} = 0 (5-137)$$

For determination of β_{21} , β_{26} and β_{27} , equations (5-124), (5-125), (5-126), (5-129), (5-130), (5-131), (5-132), (5-133), (5-136 and (5-137) among the above fourteen non-linear equations must be solved by a Newton-Raphson iteration method using a digital computer (see Appendix 1)

CHAPTER 6

STRUCTURE OF THE GENERAL SCHEMES OF OMRAC FOR A CONTINUOUS STIRRED TANK REACTOR

From Theory II: (Chapter 3: 3.1.2)

OMRAC Scheme = OMR Scheme + OAC Scheme.

For the combination of the OMR and the Oac Schemes derived in detail in Chapters 4 and 5 respectively, the structure of general OMRAC schemes for a CSTR is established and used for the further work on hybrid computer programming both for complete simulation and for on-line operation.

6.1. General Scheme I

OMR Scheme:

Optimal control action : Optimal P

Optimal control law (equation (4-34))

$$m^{*}(t) = \frac{b}{2} \left[\alpha_{12} \theta_{1}(t) + \alpha_{22} \theta_{2}(t) + \alpha_{23} \theta_{d}(t) + \alpha_{24} \theta_{L1}(t) + \alpha_{25} \theta_{L2}(t) \right]$$
(6-1)

OAC Scheme:

Optimal control action : Optimal P

Optimal control law (equation (5-27))

$$U^{*}(t) = m^{*}(t) + \frac{b}{2} R_{12} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right]$$
 (6-2)

The structure of the general scheme I of OMRAC is shown in Fig. 6.1.

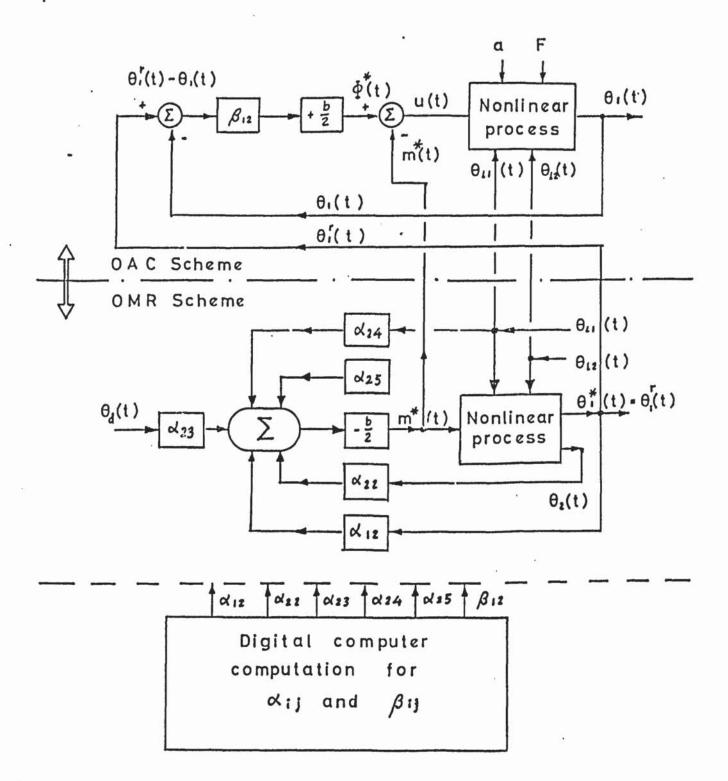


Figure 6:1 Structure of General scheme I
of OMRAC

6.2. General Scheme II

OMR Scheme:

Optimal control action: Optimal P

Optimal control law (equation (4-34)):

$$m^{*}(t) = -\frac{b}{2} \left[\alpha_{12} \theta_{1}(t) + \alpha_{22} \theta_{2}(t) + \alpha_{23} \theta_{d}(t) + \alpha_{24} \theta_{L1}(t) + \alpha_{25} \theta_{L2}(t) \right]$$
(6-2)

OAC Scheme:

Optimal control action : Optimal P + I

Optimal control law (equation (5-58)):

$$U^{*}(t) = m^{*}(t) + \frac{b}{2} \left\{ \beta_{21} \left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] + \beta_{26} \right\} \left[\left[\theta_{1}^{r}(t) - \theta_{1}(t) \right] dt \right\}$$

$$(6-3)$$

The structure of general scheme II of OMRAC is shown in Fig.6.2.

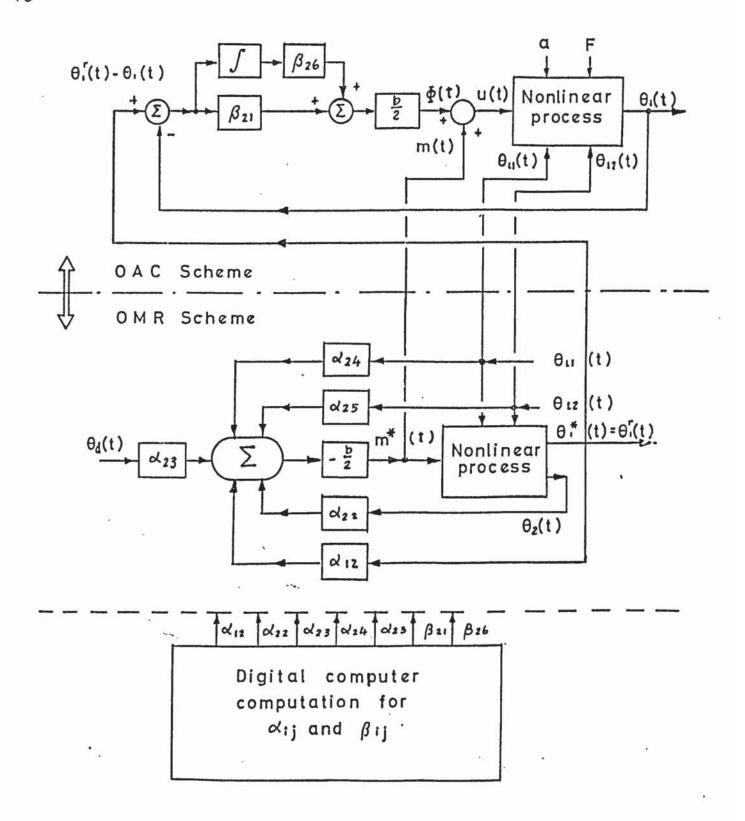


Figure 6.2 Structure of General scheme I

6.3. General Scheme III

OMR Scheme

Optimal control action: Optimal P

Optimal control law (equation (4-34)):

$$m^{*}(t) = -\frac{b}{2} \left[\alpha_{12} \theta_{1}(t) + \alpha_{22} \theta_{2}(t) + \alpha_{23} \theta_{d}(t) + \alpha_{24} \theta_{L1}(t) + \alpha_{25} \theta_{L2}(t) \right]$$
(6-1)

OAC Scheme

Optimal control action: Optimal P + I + D

Optimal control law (equation 5-100)):

$$U^{*}(t) = m^{*}(t) + \frac{b}{2} \left\{ \mathbf{B}_{21} \left[\mathbf{o}_{1}^{r}(t) - \mathbf{o}_{1}(t) \right] + \mathbf{B}_{26} \int_{t_{0}}^{t} \mathbf{o}_{1}^{r}(t) - \mathbf{o}_{1}(t) dt + \mathbf{B}_{27} \frac{d}{dt} \left[\mathbf{o}_{1}^{r}(t) - \mathbf{o}_{1}(t) \right] \right\}$$

$$(6-4)$$

The structure of the general scheme III of OMRAC is shown in Fig.6.3.

Note: The values of β_{21} and β_{26} in Optimal P + I + D are different from those in Optimal P + I, because of the different set of equations (Chapter 5).

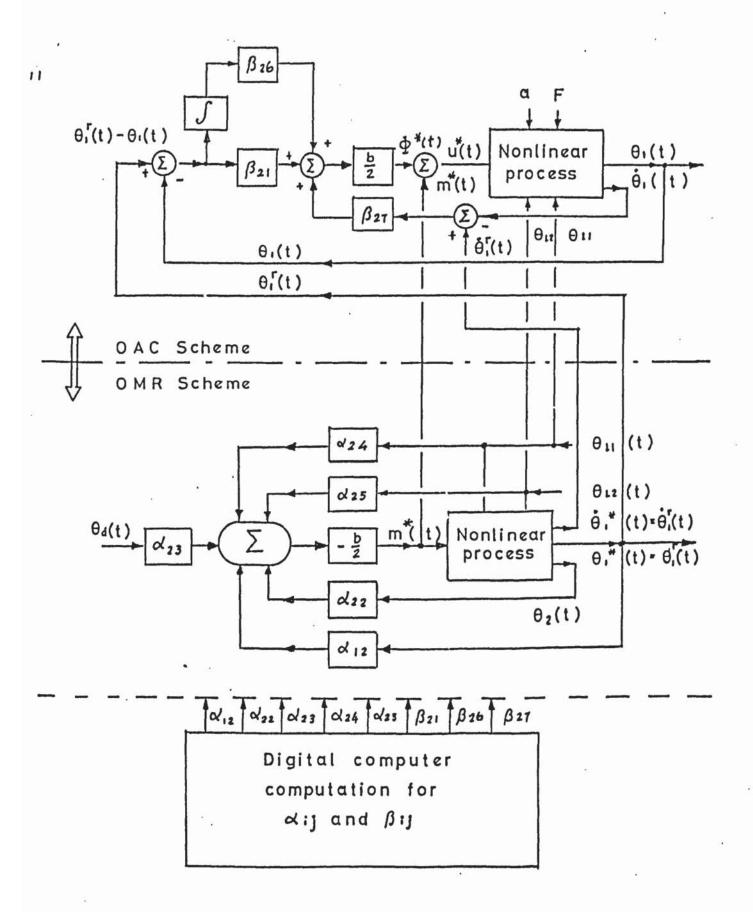


Figure 6.3 Structure of General scheme III

CHAPTER 7

COMPLETE SIMULATION ON OMRAC FOR A CSTR USING THE TR-10 AND TR-48 ANALOGUE AND HYBRID COMPUTERS

7.1. General case consideration for a partially simulated CSTR

The terms "complete simulation" and "partial simulation" have been defined by Buxton in his Ph.D.Thesis (80) (p:vii) as shown below:

Complete simulation:

This term is used when the entire process is modelled and then implemented on a computer to obtain a solution.

Partial simulation:

This term is used when some of the process exists in real plant whilst a particular part of it is chosen to be modelled and simulated on a computer. The computer operates on-line to the real equipment and the two operate together, thus representing the whole of the process for the purpose of the investigation.

The process equations of a CSTR may be rewritten as follows:

$$\frac{dC}{dt} = \frac{F}{V} (C_0 - C) - aKC \qquad (7-1)$$

$$\frac{dT}{dt} = \frac{F}{V} (T_o - T) + \frac{aKC(-\Delta H)}{\rho C_p} - \frac{Q_c}{\rho C_p V}$$
 (7-2)

$$-\frac{E}{RT}$$
where K = A e is the reaction rate (sec⁻¹) (7-3)

and the heat generation of an exothermic reaction, Q is:

$$Q_g = (-\Delta H) V aKC$$
 (7-4)

For partial simulation applied to a CSTR, equation (7-1) and part of equation (7-2) are simulated directly on the analogue computer and the heat is generated in the reactor by means of immersion heaters. The reactor temperature can be controlled by a feedback control loop containing a detecting element (thermocouple), a three mode conventional PID controller and a control valve to control the cooling water flowrate. The heat generation system using an immersion heater is designed to be actuated by a servomechansim. Complete and partial simulation for a step change applied to the reactor at the steady state was studied by means of the EAL TR-10 analogue computer and was reported by Buxton at the end of 1970.

Since for partial simulation of a CSTR, the reaction constants such as A and E in equation (7-3) can be arbitrarily selected in a certain reasonable range, other values ($-\Delta$ H), K and Q can be calculated from operating experimental data.

By using Buxton's experiments 6 and 7 (p.337 (80) the operating experimental data is shown as follows:

Ts	=	reactor temperature as steady state	=	30°C
T _c	=	reactor inlet charge temperature	=	19°C
T _{cl}	=	cooling water inlet temperature	=	19°C
Tcs	=	cooling water outlet temperature		
		at steady state	=	27°C
Cs	=	reactor concentration at steady		
		state	=	0.097 mol/litre
^m c	=	cooling water flowrate	=	2.15 litre/min
Co	=	inlet concentration	=	1.0 mol/litre
F	=	reacter charge flowrate	=	3.0 litre/min

A = constant in Arrhenius equation = $6.3 \times 10^{15} \frac{1}{\text{sec}}$

E = reaction energy, a constant = 24000 cal/mol

R = gas constant = 1.987 cal/mol.deg.K

V = reactor effective volume = 16 litre

 C_p = specific heat of reactant = 1 cal/gm.deg C

 ρ = density of reactant = 1 gm/cm³

Heat from immersion heater $Q_g = 842$ cal/sec

Reaction rate constant K = 0.032 1/sec

Change of enthalpy $(-\Delta H)$ = 18600 cal/mol.

Using the above experimental data at steady state, several simple calculations and checks can be made and are shown below:

Check on steady state concentration:

At steady state, equation (7-1) becomes:

$$0 = \frac{F}{V} (C_0 - C_s) - aKC_s$$
 (7-5).

$$K = Ae^{-\frac{E}{RT}} = 6.3 \times 10^{15} \exp \left[-\frac{24000}{1.987(273 + 30)} \right]$$

$$= 6.3 \times 10^{15} \exp (-39.8433)$$

$$= 0.0314 (1/sec)$$
 (7-6)

then

$$0 = \frac{3}{16 \times 60} (1 - C_s) - 1 \times 0.0314 \times C_s$$

...
$$C_{\rm g}$$
 = 0.08985 \simeq 0.09 mol/litre

i.e. the theoretical value of $C_s = 0.09 \text{ (mol/litre)}$ and the experimental value of $C_s = 0.097 \text{ (mol/litre)}$ 2. Check on Qg.

$$Q_{g} = \rho_{c}C_{pc}F_{c} (T_{cs} - T_{c1}) + \rho_{cp}F(T_{s} - T_{o})$$

$$= \frac{2.15 \times 1000}{60} (27-19) + \frac{3.0 \times 1000}{60} (30-19)$$

$$= 837 \text{ cal/sec.}$$

3. Check on $(-\Delta H)$

$$-\Delta H = \frac{Q_g}{V K C_s} = \frac{837}{16 \times 0.0314 \times 0.09}$$
 (7-8)

The above simple checks show quite good agreement between the partially simulated technique and the theoretical one.

From the above analysis, a general case of the research work on OMRAC for a partially simulated CSTR which was used both for complete simulation and on-line computer operation will be given below:

Operating steady state conditions:

$$C_s = 0.09 \text{ mol/litre}$$

$$T_s = 30^{\circ}C$$

Operating normal inlet conditions:

$$C_0 = 1.0 \text{ mol/litre}$$

Process physical constants:

$$\rho = 1.0 \text{ mol/cm}^3$$

$$C_p = 1.0 \text{ cal/g.deg } C$$

Reactant constants

 $A = 6.3 \times 10^{15} \text{ 1/sec.}$

E = 24,000 cal/mol

R = 1.987 cal/mol deg K

7.2. Magnitude scaling and time scaling

All analogue and hybrid computer programming must be unified and represented by scaled computer variables and related equations through all the work both for complete simulation and on-line computer operation (see Part II)

7.2.1. Magnitude scaling

The estimated maximum value of variables and their scaled computer variables are tabulated in Table 7.1.

Table 7.1. Magnitude scaling

Pro	cess variables	Estimated max. value	Scaled computer variables (machine unit or mu) (1 mu = 10 volt)
C (mol/litre)	C _m = 1.0 (mol/litre)	
Co	(mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} \frac{C}{\Theta_{m}} \end{array}\right]$
Cos	(mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} c_{os} \\ c_{m} \end{array}\right]$
C _{s,}	(mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} \frac{C_{B}}{C_{m}} \end{array}\right]$
° _r	(mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} \frac{c_r}{c_m} \end{array}\right]$

Table 7.1. Magnitude scaling (continued)

Process variable	Estimated max. value	Scaled computer variable (mu)
C _{rs} (mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} C_{rs} \\ C_{m} \end{array}\right]$
C _d (mol/litre)	$C_m = 1.0 (mol/litre)$	$\left[\begin{array}{c} \frac{c_d}{c_m} \end{array}\right]$
C _{ds} (mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} C_{ds} \\ C_{m} \end{array}\right]$
$\Delta C = 0$ (mol/litre)	C _m = 1.0 (Mol/litre)	$\left[\begin{array}{c} \underline{\mathbf{A}}\underline{\mathbf{C}} \\ \overline{\mathbf{C}}_{\underline{\mathbf{m}}} \end{array}\right]$
$\Delta C_0 = \theta_2 \pmod{\text{litre}}$	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} \Delta^{C}_{o} \\ \overline{C}_{m} \end{array}\right]$
ΔC _r (mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} \Delta^{C}_{r} \\ \overline{C}_{m} \end{array}\right]$
ΔC _d (mol/litre)	C _m = 1.0 (mol/litre)	$\left[\begin{array}{c} \Delta C_{\underline{d}} \\ \overline{C_{\underline{m}}} \end{array}\right]$
<pre>. c (mol/litre-sec)</pre>	$\dot{C}_{m} = 0.1 (mol/litre-sec$	$(c) \left[\begin{array}{c} \dot{C}_{m} \\ \dot{C}_{m} \end{array} \right]$
<pre>c r (mol/litre-sec)</pre>	\dot{C}_{m} = 0.1 (mol/litre-sec	$(\frac{\dot{c}_r}{c_m})$
Δc (mol/litre-sec)	\dot{C}_{m} = 0.1 (mol/litre-sec	$(a) \left[\begin{array}{c} \frac{\Delta \dot{c}}{\dot{c}_{m}} \end{array}\right]$
T (°C)	T _m = 100 (°C)	$\begin{bmatrix} \frac{\mathbf{T}}{\mathbf{T_m}} \end{bmatrix}$
T (°C)	T _m ' = 40 (°C)	$\left[\begin{array}{c} \frac{\mathbf{T}}{\mathbf{T}_{\mathbf{m}}}, \end{array}\right]$
T (°C)	T _m " =39,25(°C)	$\left[\begin{array}{c} \frac{T}{T_{m}} \end{array}\right]$
T _o (°C)	$T_m = 100 (^{\circ}C)$	$\left[\begin{array}{c} \frac{\mathbf{T_o}}{\mathbf{T_m}} \end{array}\right]$
T _s (°C)	$T_m = 100 (^{\circ}C)$	$\left[\begin{array}{c} \frac{T_{s}}{T_{m}} \end{array}\right]$
ΔT (°C/sec)	T _m = 1.0 (°C/sec)	$\left[\begin{array}{c} \Delta \dot{T} \\ \dot{T}_{m} \end{array}\right]$

Table 7.1. Magnitude scaling (continued)

Process variabl	Le Estimated Max.Value	e Scaled computer variable (mu)
ΔT (°C)	T _m = 100 (°C)	$\left[\begin{array}{c} \underline{\Delta}\underline{T} \\ \underline{T}_{\underline{m}} \end{array}\right]$
T (°C/sec)	$\dot{T}_{m} = 1.0$ (°C/sec	$\left[\begin{array}{c}\frac{\mathbf{\dot{T}}}{\mathbf{\dot{T}_{m}}}\end{array}\right]$
K (1/sec)	$K_{m} = 0.1$ (1/sec)	$\left[\begin{array}{c} \frac{K}{K_m} \end{array}\right]$
F (litre/min)	$F_{m} = 5.0 (litre/min)$	$\left[\begin{array}{c} \frac{F}{F_m} \end{array}\right]$
a (dimensionles	a _m = 1.0 (dimensional less)	$n-\left[\begin{array}{c} \frac{a}{a_m} \end{array}\right]$
Qc (Kcal/min) (60 Kcal/h)	or Q _{cm} = 100 (60 Kcal,	$/h$) $\left[\frac{Q_c}{Q_{cm}}\right]$
Q (Kcal/min) (60 Kcal/h)	or Q _{cm} = 100 (60 Kcal,	$/h$) $\left[\frac{Q_{cs}}{Q_{cm}}\right]$
m* (Kcal/min) (60 Kcal/h)	or Q _{cm} = 100 (60 Kcal,	h) $\left[\frac{m^*}{Q_{cm}}\right]$
U* (Kcal/min) (60 Kcal/h)		$/h$) $\left[\frac{U^*}{Q_{cm}}\right]$
F _c (litre/min)	F _{cm} = 10 (litre/mi	$ \left[\begin{array}{c} F_{c} \\ \hline F_{cm} \end{array} \right] $
Q (Kcal/h x 10	$Q_{gm} = 10 (Kcal/h x)$	10^{-3}) $\left[\begin{array}{c} Q_g \\ Q_{gm} \end{array}\right]$

7.2.2. Time Scaling

$$T = \beta t (7-9)$$

where

t = machine time (sec)

t = process real time (sec)

β = time scale factor

For complete simulation work:

$$B = 0.1$$

For on-line computer operation :

7.3. Modified Linearisation coefficients

Linearised equations (4-6) and (4-7) which omitted T_0 term, can be written as follows:

$$\Delta \dot{C} = a_{11} \Delta C + a_{12} \Delta T + d_{11} \Delta C_{0}$$
 (7-10)

$$\Delta \dot{T} = a_{21} \Delta C + a_{22} \Delta T + b \Delta Q_{c}$$
 (7-11)

The scaled computer equations based on the information contained in Table 7.1, are

$$\begin{bmatrix} \Delta \dot{c} \\ \dot{c}_{m} \end{bmatrix} = \begin{pmatrix} \frac{a_{11}^{C}_{m}}{\dot{c}_{m}} \end{pmatrix} \begin{bmatrix} \Delta c \\ \dot{c}_{m} \end{bmatrix} + \begin{pmatrix} \frac{a_{12}^{T}_{m}}{\dot{c}_{m}} \end{pmatrix} \begin{bmatrix} \Delta T \\ \dot{T}_{m} \end{bmatrix} + \begin{pmatrix} \frac{d_{11}^{C}_{m}}{\dot{c}_{m}} \end{pmatrix} \begin{bmatrix} \Delta c \\ \dot{c}_{m} \end{bmatrix}$$

$$\begin{bmatrix} \Delta \dot{T} \\ \dot{T}_{m} \end{bmatrix} = \begin{pmatrix} \frac{a_{21} \cdot c_{m}}{\dot{T}_{m}} \end{pmatrix} \begin{bmatrix} \Delta c \\ \dot{c}_{m} \end{bmatrix} + \begin{pmatrix} \frac{a_{22} \cdot T_{m}}{\dot{T}_{m}} \end{pmatrix} \begin{bmatrix} \Delta T \\ \dot{T}_{m} \end{bmatrix} + \begin{pmatrix} \frac{b \cdot Q_{cm}}{\dot{T}_{m}} \end{pmatrix} \begin{bmatrix} \Delta Q_{cm} \\ \dot{T}_{m} \end{bmatrix}$$

$$(7-13)$$

The original linearised coefficients of equations (7-10) and (7-11) can be determined by given constants shown at the end of Section 1, then:

$$a_{11} = -\frac{F}{V} - A \exp(-\frac{E}{RT_S})$$

$$= -(\frac{3}{60} \times \frac{1}{16}) - 0.0314 = -0.0345 \qquad (7-14-1)$$

$$a_{12} = \left(-\frac{E}{RT_0^2}\right) A \exp\left(-\frac{E}{RT_S}\right) . C_S$$

$$= \frac{39.8433}{303} \times 0.0314 \times 0.09 = 0.00037 \qquad (7-14-2)$$

$$a_{121} = \frac{(-\Delta H) \text{ A exp } (-\frac{E}{RT_s})}{\rho c_p \times 1000}$$

$$= \frac{18511 \times 0.0314}{1 \times 1 \times 1000} = 0.5812$$
 (7-14-3)

$$a_{22} = -\frac{F}{V} - \frac{(-\Delta H) \text{ A exp } (-\frac{E}{RT_s^2}) \text{ C}_s}{\rho \text{ C}_p}$$

$$= -(\frac{3}{60} \times \frac{1}{60}) - (\frac{18511 \times 0.0314}{1 \times 1 \times 1000}) (\frac{39.8433}{303}) (0.09)$$

$$= -0.00995 \cong -0.01 \qquad (7-14-4)$$

b =
$$-\frac{1}{\rho c_p V}$$
 · $\frac{1}{60}$ = $\frac{-1}{1 \times 1 \times 16 \times 60}$ = 0.0011 (7-14-5)

$$d_{11} = \frac{F}{V} \cdot \frac{1}{60} = \frac{3}{16} \cdot \frac{1}{60} = 0.003$$
 (7-14-6)

Substituting all of the above calculated coefficients and estimated maximum values into equations (7-12) and (7-13) then gives:

$$\begin{bmatrix} \frac{\Delta \dot{c}}{\dot{c}_{m}} \end{bmatrix} = (\frac{-0.0345 \times 1.0}{0.1}) \begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix} + (\frac{0.00037 \times 100}{0.1}) \begin{bmatrix} \frac{\Delta T}{T_{m}} \end{bmatrix} + (\frac{0.003 \times 1.0}{0.1}) \begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix}$$

$$= -(0.345) \begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix} + 0.37 \begin{bmatrix} \frac{\Delta T}{C_{m}} \end{bmatrix} + 0.03 \begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix}$$
 (7-15)

$$\begin{bmatrix} \frac{\Delta T}{T_{m}} \end{bmatrix} = \left(\frac{0.58 \times 1}{1}\right) \begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix} + \left(\frac{-0.01 \times 100}{1.00}\right) \begin{bmatrix} \frac{\Delta T}{T_{m}} \end{bmatrix}$$

$$+ \left(\frac{-0.0011 \times 100}{1.0}\right) \begin{bmatrix} \frac{\Delta Q_{c}}{Q_{cm}} \end{bmatrix}$$

$$= + \left(0.58\right) \begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix} - \left(1.0\right) \begin{bmatrix} \frac{\Delta T}{T_{m}} \end{bmatrix} - \left(0.11\right) \begin{bmatrix} \frac{\Delta Q_{c}}{Q_{cm}} \end{bmatrix}$$
 (7-16)

From scaled computer variable equations (7-15) and (7-16) the modified linearised coefficients will be:

The above set of modified linearisation coefficients can be used as D(i) defined in Appendix 1 for all digital computer programming as "READ INPUT" to compute all optimal control law coefficients aij and Bij both for the OMR scheme and the OAC scheme.

Then all computed values of a ij and B ij will be potentiometer setting values in the analogue and hybrid computer programming and is discussed in the following section.

7.4. Programming the computer

7.4.1. OMR Scheme computer programming

From equations (7-1) and (7-2) and the corresponding equations (7-19) and (7-20), the scaled computer variable

equations of the OMR scheme are shown below:

$$\begin{bmatrix} \frac{\dot{c}}{\dot{c}_{m}} \end{bmatrix} = \left(\frac{F}{60 \cdot V}\right) \left(\frac{C_{m}}{\dot{c}_{m}}\right) \left[\frac{C_{o}}{C_{m}}\right] - \left(\frac{F}{60V}\right) \left(\frac{C_{m}}{C_{m}}\right) \left[\frac{C}{C_{m}}\right]$$

$$- \left(\frac{a_{s} K_{m} C_{m}}{\dot{c}_{m}}\right) \left[\frac{K}{K_{m}}\right] \left[\frac{C}{C_{m}}\right]$$

$$= \left(\frac{3}{60 \times 16}\right) \left(\frac{1}{1}\right) \left[\frac{c_{o}}{C_{m}}\right] - \left(\frac{3}{60 \times 16}\right) \left(\frac{1}{1}\right) \left[\frac{C}{C_{m}}\right]$$

$$- \left(\frac{1 \times 1 \times 1}{0 \cdot 1}\right) \left[\frac{K}{K_{m}}\right] \left[\frac{C}{C_{m}}\right]$$

$$(7-18)$$

$$\begin{bmatrix} \frac{\dot{T}}{\hat{T}_{m}} \end{bmatrix} = \left(\frac{F}{60V} \right) \left(\frac{T_{m}}{\hat{T}_{m}} \right) \left[\frac{T_{0}}{T_{m}} \right] - \left(\frac{F}{60V} \right) \left(\frac{T_{m}}{\hat{T}_{m}} \right) \left[\frac{T_{m}}{T_{m}} \right]$$

$$- \left(\frac{a_{s} K_{m} C_{m} H}{C_{p} \hat{T}_{m} \times 1000} \right) \left[\frac{K}{K_{m}} \right] \left[\frac{C}{C_{m}} \right]$$

$$- \left(\frac{Q_{cm}}{C_{p} V 60 \cdot \hat{T}_{m}} \right) \left[\frac{Q_{c}}{Q_{cm}} \right]$$

$$= \left(\frac{3}{60 \times 16} \right) \left(\frac{100}{1 \cdot 0} \right) \left[\frac{T_{0}}{T_{m}} \right] - \left(\frac{3}{60 \times 16} \right) \left(\frac{100}{1 \cdot 0} \right) \left[\frac{T}{T_{m}} \right]$$

$$- \left(\frac{1 \cdot 0 \times 0 \cdot 1 \times 1 \cdot 0 \times 18511}{1 \cdot 0 \times 1 \cdot 0 \times 100 \times 1000} \right) \left[\frac{K}{K_{m}} \right] \left[\frac{C}{C_{m}} \right]$$

$$- \left(\frac{100}{1 \cdot 0 \times 1 \cdot 0 \times 16 \times 60 \times 100} \right) \left[\frac{Q_{c}}{Q_{c}} \right]$$

$$(7-19)$$

Simplifying equations (7-18) and (7-19) gives :

$$\begin{bmatrix} \frac{\dot{c}}{\dot{c}_{m}} \end{bmatrix} = 0.031 \begin{bmatrix} \frac{c_{o}}{c_{m}} \end{bmatrix} - 0.031 \begin{bmatrix} \frac{c}{c_{m}} \end{bmatrix} - 1.0 \begin{bmatrix} \frac{K}{K_{m}} \end{bmatrix} \begin{bmatrix} \frac{c}{c_{m}} \end{bmatrix}$$

$$\begin{bmatrix} \frac{\dot{T}}{\dot{T}_{m}} \end{bmatrix} = 0.31 \begin{bmatrix} \frac{T_{o}}{T_{m}} \end{bmatrix} - 0.31 \begin{bmatrix} \frac{T}{T_{m}} \end{bmatrix} - 1.85 \begin{bmatrix} \frac{K}{K_{m}} \end{bmatrix} \begin{bmatrix} \frac{c}{c_{m}} \end{bmatrix}$$

$$- 0.11 \begin{bmatrix} \frac{Q_{c}}{Q_{c}} \end{bmatrix}$$

$$(7-21)$$

The optimal control law of the OMR scheme from Chapter 6 equation (6-1) gives:

$$\left[\frac{Q_{c}}{Q_{cm}}\right] = \left[\frac{Q_{cs}}{Q_{cm}}\right] + \left[\frac{m^*}{Q_{cm}}\right]; \qquad (7-22)$$
and
$$\left[\frac{m^*}{Q_{cm}}\right] = -\frac{b'}{2} \left(\alpha_{12}\left[\frac{\Delta C}{C_{m}}\right] + \alpha_{22}\left[\frac{\Delta T}{T_{m}}\right] + \alpha_{23}\left[\frac{\Delta C_{d}}{C_{m}}\right] + \alpha_{24}\left[\frac{\Delta C_{o}}{C_{m}}\right] \qquad (7-23)$$

where:

$$\begin{bmatrix} \frac{\Delta C}{C_{m}} \end{bmatrix} = \begin{bmatrix} \frac{C}{C_{m}} \end{bmatrix} + \begin{bmatrix} \frac{C_{s}}{C_{m}} \end{bmatrix} = \begin{bmatrix} \frac{C}{C_{m}} \end{bmatrix} - \begin{bmatrix} \frac{.09}{1.0} \end{bmatrix} = \begin{bmatrix} \frac{C}{C_{m}} \end{bmatrix} - 0.9 \text{ w}$$

$$(7-24)$$

$$\begin{bmatrix} \frac{\Delta T}{T_{m}} \end{bmatrix} = \begin{bmatrix} \frac{T}{T_{m}} \end{bmatrix} - \begin{bmatrix} \frac{T_{s}}{T_{m}} \end{bmatrix} = \begin{bmatrix} \frac{T}{T_{m}} \end{bmatrix} - \begin{bmatrix} \frac{30}{100} \end{bmatrix} = \begin{bmatrix} \frac{T}{T_{m}} \end{bmatrix} - 3.0 \text{ v}$$
(7-25)

$$\begin{bmatrix} \frac{\Delta C_{d}}{C_{m}} \end{bmatrix} = \begin{bmatrix} \frac{C_{d}}{C_{m}} \end{bmatrix} - \begin{bmatrix} \frac{C_{ds}}{C_{m}} \end{bmatrix} = \begin{bmatrix} \frac{C_{d}}{C_{m}} \end{bmatrix} - \begin{bmatrix} \frac{.09}{1.0} \end{bmatrix} = \begin{bmatrix} \frac{C_{d}}{C_{m}} \end{bmatrix} - 0.9 \text{ v}$$
(7-26)

$$\left[\begin{array}{c} \Delta C_{o} \\ \overline{C_{m}} \end{array} \right] = \left[\begin{array}{c} C_{o} \\ \overline{C_{m}} \end{array} \right] + \left[\begin{array}{c} C_{os} \\ \overline{C_{m}} \end{array} \right] = \left[\begin{array}{c} C_{o} \\ \overline{C_{m}} \end{array} \right] - \left[\begin{array}{c} 1.0 \\ 1.0 \end{array} \right] = \left[\begin{array}{c} C_{o} \\ \overline{C_{m}} \end{array} \right] - 10 \text{ V}$$

$$(7 \% 27)$$

$$\left[\begin{array}{c} Q_{\text{CS}} \\ \overline{Q}_{\text{cm}} \end{array}\right]$$
 calculated by trial and error from equations (7-20)

and (7-21) at steady state, is

$$\left[\frac{Q_{CS}}{Q_{CM}}\right] = -0.753 \text{ mu} = -7.53 \text{ volt.}$$

Using the above scaled computer variable equations (7-20) to (7-27) the computer diagram of the OMR scheme is shown in Fig. 7.1.

7.4.2. OAC scheme computer programming:

Process scaled computer variable equations:

$$\begin{bmatrix} \frac{\dot{c}}{\dot{c}_{m}} \end{bmatrix} = \begin{pmatrix} \frac{F_{m}}{60 \text{ V}} \end{pmatrix} \begin{pmatrix} \frac{C_{m}}{\dot{c}_{m}} \end{pmatrix} \begin{bmatrix} \frac{C_{0}}{C_{m}} \end{bmatrix} \begin{bmatrix} \frac{F}{F_{m}} \end{bmatrix} - \begin{pmatrix} \frac{F_{m}}{60 \text{V}} \end{pmatrix} \begin{pmatrix} \frac{C_{m}}{\dot{c}_{m}} \end{pmatrix} \begin{bmatrix} \frac{F}{F_{m}} \end{bmatrix} \end{bmatrix}$$

$$- \begin{pmatrix} \frac{a_{m}}{c_{m}} & \frac{K_{m}}{c_{m}} & \frac{C_{m}}{c_{m}} \end{bmatrix} \begin{bmatrix} \frac{A_{m}}{A_{m}} \end{bmatrix} \begin{bmatrix} \frac{K_{m}}{K_{m}} \end{bmatrix} \begin{bmatrix} \frac{C_{m}}{C_{m}} \end{bmatrix} \begin{bmatrix} \frac{F_{m}}{F_{m}} \end{bmatrix}$$

$$- \begin{pmatrix} \frac{5}{60 \times 16} \end{pmatrix} \begin{pmatrix} \frac{1}{0.1} \end{pmatrix} \begin{pmatrix} \frac{1}{0.1} \end{pmatrix} \begin{pmatrix} \frac{1}{0.1} \end{pmatrix} \begin{pmatrix} \frac{1}{0.1} \end{pmatrix} \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} - \begin{pmatrix} \frac{5}{60 \times 16} \end{pmatrix} \begin{pmatrix} \frac{1}{0.1} \end{pmatrix} \begin{pmatrix} \frac{C_{m}}{C_{m}} \end{pmatrix} \begin{bmatrix} \frac{F_{m}}{F_{m}} \end{bmatrix}$$

$$- \begin{pmatrix} \frac{1.0 \times 0.1 \times 1.0}{T_{m}} \end{pmatrix} \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} - \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{T_{m}}{T_{m}} \end{pmatrix} \begin{pmatrix} \frac{T_{m}}{T_{m}} \end{pmatrix} \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix}$$

$$- \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{A_{H}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{K_{m}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{C_{m}}{T_{m}} \end{pmatrix} \begin{pmatrix} \frac{F_{m}}{F_{m}} \end{pmatrix} \begin{pmatrix} \frac{C_{m}}{T_{m}} \end{pmatrix} \begin{pmatrix} \frac{C_{m}}{T_{m}} \end{pmatrix}$$

$$- \begin{pmatrix} \frac{Q_{cm}}{P_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} \end{pmatrix} \begin{pmatrix} \frac{Q_{c}}{Q_{cm}} \end{pmatrix}$$

$$- \begin{pmatrix} \frac{Q_{cm}}{P_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} \end{pmatrix} \begin{pmatrix} \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} \end{pmatrix} \begin{pmatrix} \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} \end{pmatrix} \begin{pmatrix} \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} & \frac{1}{N_{c}} \end{pmatrix} \begin{pmatrix} \frac{1}{N_{c}} & \frac{1}{N_{c$$

Simplifying equations (7-28) and (7-29) gives

$$\left[\begin{array}{c} \frac{\dot{C}}{\dot{C}_{m}} \right] = 0.052 \left[\begin{array}{c} \frac{C}{C_{m}} \end{array} \right] \left[\begin{array}{c} \frac{F}{F_{m}} \end{array} \right] - 0.052 \left[\begin{array}{c} \frac{C}{C_{m}} \end{array} \right] \left[\begin{array}{c} \frac{F}{F_{m}} \end{array} \right]$$

$$- 1.0 \left[\begin{array}{c} \frac{a}{a_{m}} \end{array} \right] \left[\begin{array}{c} \frac{K}{K_{m}} \end{array} \right] \left[\begin{array}{c} \frac{C}{C_{m}} \end{array} \right]$$

$$(7-30)$$

Optimal control law for the OAC scheme:

From Chapter 6, equations (6-2), (6-3) and (6-4) give the following relationship which is developed below for the combinations of control modes used in the work.

Optimal P control:

$$\left[\begin{array}{c} \frac{U^*}{Q_{cm}} \right] = \left[\begin{array}{c} \frac{m^*}{Q_{cm}} \right] + 0.055 \, \Omega_{12} \left[\left[\frac{\Delta C_r}{C_m} \right] - \left[\begin{array}{c} \frac{\Delta C}{C_m} \end{array} \right] \right)$$
 (7.33)

Now
$$\left[\frac{\Delta C_r}{C_m}\right] = \left[\frac{C_r}{C_m}\right] - \left[\frac{C_{rs}}{C_m}\right]$$
 (7-34)

$$\left[\begin{array}{c} \frac{\Delta C}{C_{m}} \end{array}\right] = \left[\begin{array}{c} \frac{C}{C_{m}} \end{array}\right] - \left[\begin{array}{c} \frac{C}{C_{m}} \end{array}\right] \tag{7-35}$$

and
$$\left[\frac{C_{rs}}{C_m}\right] = \left[\frac{C_s}{C_m}\right]$$
 (7-36)

$$\cdot \cdot \cdot \left[\frac{\mathbf{U}^*}{\mathbf{Q}_{cm}} \right] = \left[\frac{\mathbf{m}^*}{\mathbf{Q}_{cm}} \right] + 0.055 \, \mathfrak{g}_{12} \left[\left[\frac{\mathbf{C}_r}{\mathbf{C}_m} \right] - \left[\frac{\mathbf{C}}{\mathbf{C}_m} \right] \right] (7-37)$$

2. Optimal P + I control

$$\begin{bmatrix} \frac{U^*}{Q_{cm}} \end{bmatrix} = \begin{bmatrix} \frac{m^*}{Q_{cm}} \end{bmatrix} + 0.055 \left[\mathfrak{S}_{21} \left(\begin{bmatrix} \frac{C_r}{C_m} \end{bmatrix} - \begin{bmatrix} \frac{C}{C_m} \end{bmatrix} \right) + \mathfrak{B}_{26} \int_{t_0}^{t} \left(\begin{bmatrix} \frac{C_r}{C_m} \end{bmatrix} - \begin{bmatrix} \frac{C}{C_m} \end{bmatrix} \right) dt \right]$$
(7-58)

3. Optimal P + I + D Control

$$\begin{bmatrix} \frac{U^*}{Q_{cm}} \end{bmatrix} = \begin{bmatrix} \frac{m^*}{Q_{cm}} \end{bmatrix} + 0.055 \begin{bmatrix} B_{21} \left(\frac{C_r}{C_m} \right) - \left[\frac{C}{C_m} \right] \right) \\
+ B_{26} \int_{t_0}^{t} \left(\left[\frac{C_r}{C_m} \right] - \left[\frac{C}{C_m} \right] \right) dt \\
+ B_{27} \left(\left[\frac{C_r}{C_m} \right] - \left[\frac{C}{C_m} \right] \right)$$
(7-39)

Using the above scaled computer variable equations (7.30), (7-31), (7-32), (7-37), (7-38) and (7-39), the computer diagram of the OAC scheme is shown in Fig. 7.2.

The computer diagram of the optimal PID control law is shown in Fig.7.3

By using the same equations (7-22) to (7-27), the computer diagram for the unadapted optimal control operation is shown in Fig. 7.4.

The computer diagram for performance response is shown in Fig. 7.5. Performance response (PR) is defined as the integral of the response square error

i.e.
$$PR = \int_{t_0}^{t} \left[\left[\frac{c_r}{c_m} \right] - \left[\frac{c}{c_m} \right] \right]^2 dt$$
 (7-40)

and is used in "Optimal Adaptivity" for quantitative analysis of OMRAC (See Chapter 11, Part II)

The higher and lower limits of constraint can be estimated from Buxton's experimental data at steady state (Section 1)

$$a \leqslant \left[\frac{U^*}{Q_{cm}}\right] \leqslant b \tag{7-41}$$

where

$$a = 1.72 \text{ volt}$$
 $b = + 6.28 \text{ volt}$

The computer diagram for optimal control law constraints is shown in Fig. 7.6.

7.4.3. VDGF Programming on
$$\left[\frac{T}{T_m}\right]$$
 vs. $\left[\frac{K}{K_m}\right]$

The Arrhenius equation (7-3) is used both for the OMR scheme and the OAC scheme and should be carefully programmed as follows:

From equation (7-3):

$$K = 6.3 \times 10^5 \exp \left(-\frac{24000}{1.987(273 + T)}\right)$$
 (7-42)

Let

$$K_{m} = A \exp \left(-\frac{E}{RT_{m}}\right)$$
 where $T_{m}' = K$ (7-43)

$$T_{m}' = 40^{\circ}C = 317^{\circ}K$$

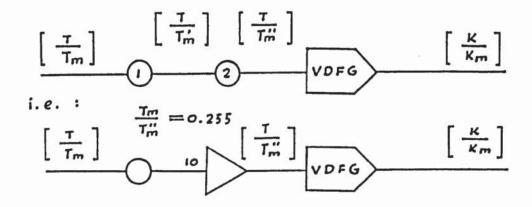
then

$$\frac{K}{K_{m}} = \exp \left(\frac{24000}{1.987 \times 313} - \frac{24000}{1.987 (273 + T)} \right) (7-44)$$

Programming of equations (7-42) and (7-44) on the digital computer is shown in Appendix 1-10 and 1-11 and from the computer results:

$$T = 39^{\circ}C$$
, $K = 0.969$
 $T_{m}' = 40^{\circ}C$, $K = 0.1097$
 $T_{m}'' = 39.25^{\circ}C$, $K = 0.10$

Then the VDFG can be programmed as follows



VDFG - 2 on TR-48 was programmed for the OMR scheme

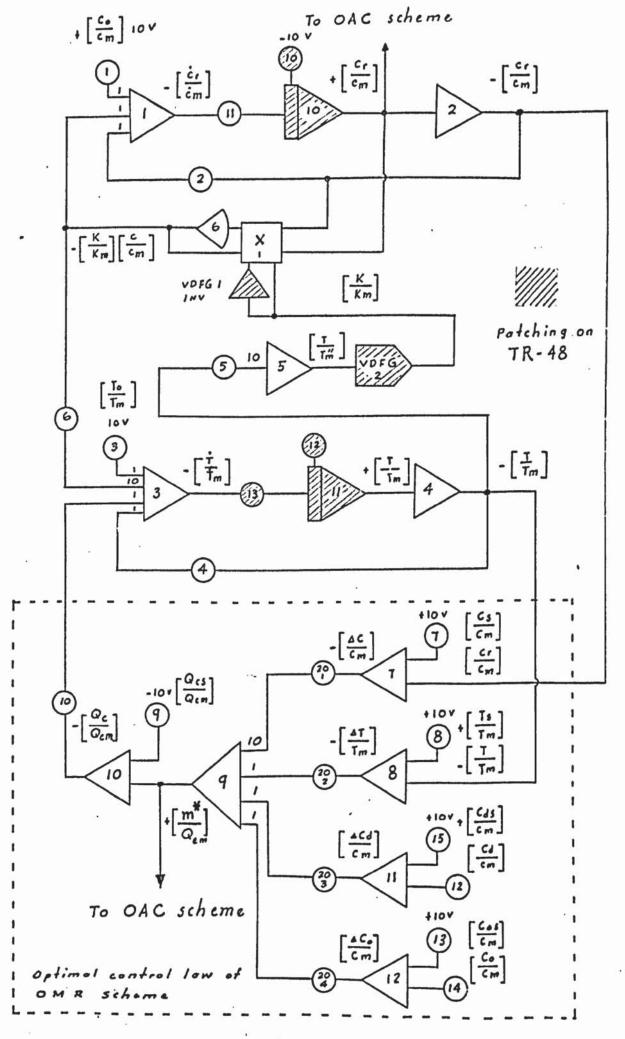
VDFG - 1 on TR-48 was programmed for the OAC scheme

(see Appendix Fig. A3.1)

7.5. Potentiometer and Amplifier assignments

Potentiometer and amplifier assignments of the overall OMRAC scheme are tabulated as follows: -

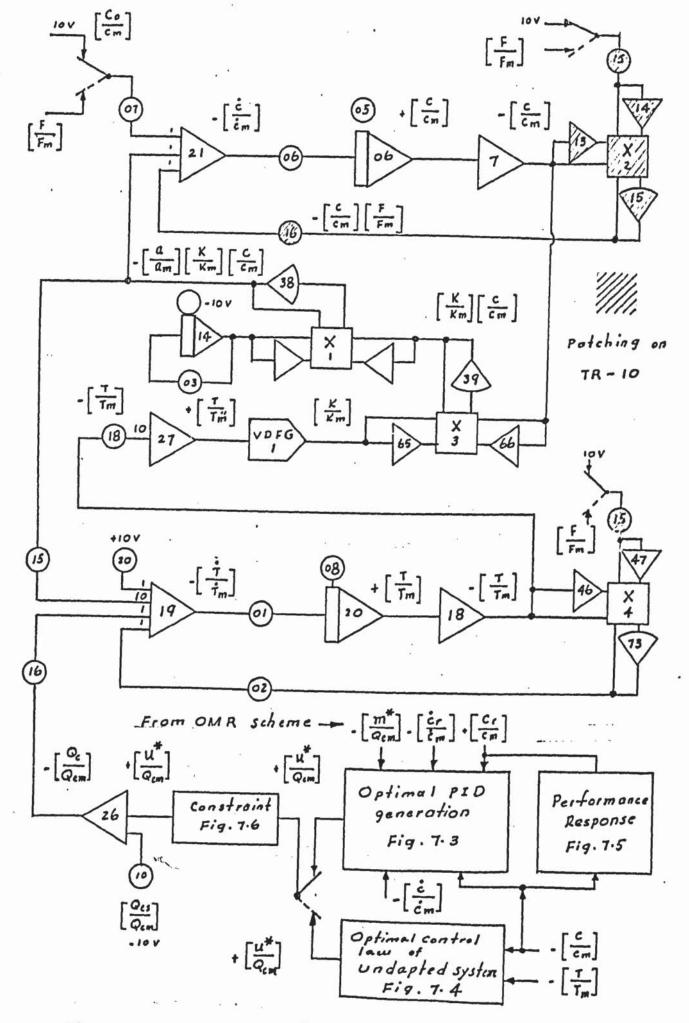
- Table 7.2. Potentiometer setting assignment sheet for the OMR scheme (Fig. 7.1)
 - Table 7.3. Amplifier Assignment sheet for the OMR scheme (Fig.7.1).
 - Table 7.4. Potentiometer setting assignment sheet for the OAC scheme (Fig.7.2)
 - Table 7.5. Potentiometer setting assignment sheet for the OAC scheme (Figs. 7.3, 7.4, 7.5, and 7.6)
 - Table 7.6. Amplifier Assignment sheet for the OAC scheme (Fig.7.2)
 - Table 7.7. Amplifier assignment sheet for the OAC scheme (Figs. 7.3, 7.4, 7.5 and 7.6).



12

Figure 7.1 Compute diagram of OMR scheme

- 129 -



13

Figure 7.2 Computer diagram of OAC scheme

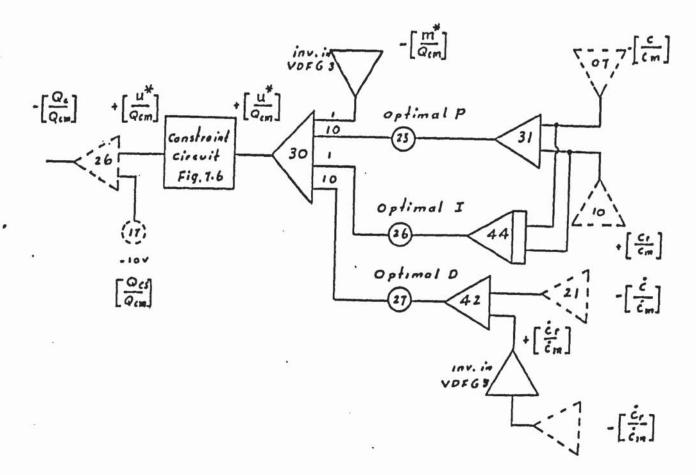


Figure 7.3 Computer diagram of optimal PID

control law generation

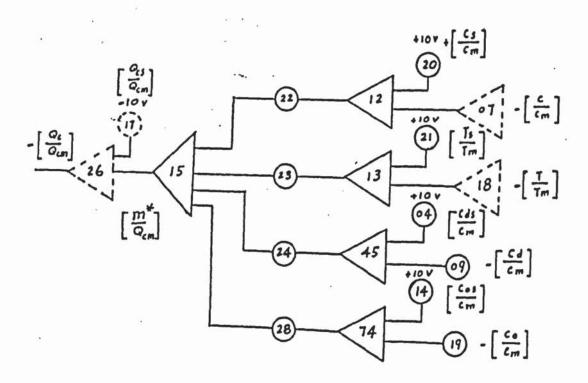


Figure 7.4 Computer diagram of OMR optimal

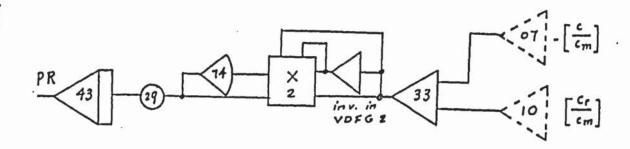


Figure 7.5 Computer diagram of performance response (PR)

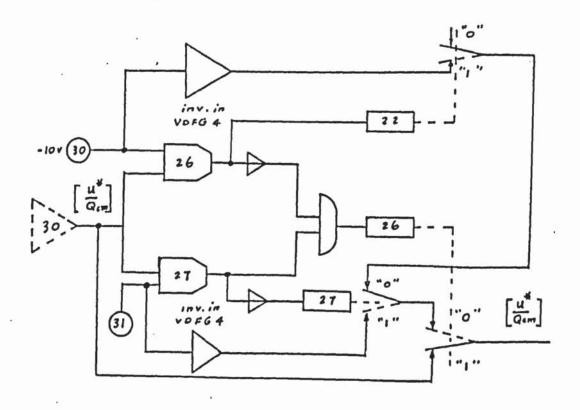


Figure 7.6 Computer diagram of optimal

TABLE 7.2.

Potentiometer assignment sheet for the OMR Scheme

(Fig. 7.1)

Computer used	Pot No.	Parameter description	Setting static check	Notes
TR-10	ı	(A)	0.031	eq.(7-20)
11	2		0.031	eq. (7-20)
11	3	$\left[\frac{T_o}{T_m}\right] \times 0.31$	0.062	eq. (7-21)
11	4	*	0.31	eq. (7-21)
"	5		0.255	Section 7.4.3.
n,	6	(A) (A) (A) (A) (A)	0.185	eq. (7-21)
u	7	$\left[\frac{c_s}{c_m}\right]/10$	0.09	eq. (7-24)
"	8	$\left[\frac{T_s}{T_m}\right]/10$	0.30	eq. (7-25)
u.	9	$\left[\frac{Q_{cs}}{Q_{cm}}\right]$ /10	0.753	eq. (7-22)
11	10		0.11	eq. (7-21)
"	11	$\left[\frac{C_{ds}}{C_{m}}\right]/10$	0.09	eq. (7-26)
11	12	$\left[\frac{c_d}{c_m}\right]$ /10	0.09	Let C _d be unchanged
11	13	$\left[\frac{C_{os}}{C_{m}}\right]/10$	1.0	eq. (7-27)
."	14	$\left[\frac{C_o}{C_m}\right]/10$	1.0	Let Cobe unchanged
"	20-1 .	0.055	0.28	See Appendix 2.7
11	20-2	0.055 22	0.8	11
**	20-3			n
"	20-4	0.055 24		**

TABLE 7.2. (continued)

		######################################		
Computer used	Pot No.	Parameter description	Setting static check	Notes
TR-48	10	$\left[\frac{C(o)}{C_{m}}\right] / 10$	0.135	
11	11	(cm/cmu)	1.0	B = 0.1
u.	12	$\left[\frac{T(o)}{T_{m}}\right]/10$	0.33	
"	13	(T/Tm B)	0.1	B = 0.1
		**		

î.

TABLE 7.3.

Amplifier assignment sheet for the OMR scheme (Fig.7.1)

Computer	AMP No.	FB	Output variables	Static check (Volt)	Notes
TR-48	- 10	ſ	+ [C]	+ 1.35	
n	11	ſ	$+\left[\begin{array}{c} \frac{\mathbf{T}}{\mathbf{T}_{\mathbf{m}}} \end{array}\right]$	+ 3.3	
TR-10	1	Σ	$-\left[\begin{array}{c} \frac{\dot{c}}{\dot{c}_{m}} \end{array}\right]$	-(.3104261) = 0.342	
"	2	Inv.	$-\left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$	- 1.35	
11	3	Σ	$-\left[\begin{array}{c} \frac{\dot{\mathtt{T}}}{\dot{\mathtt{T}}_{\mathtt{m}}} \end{array}\right]$	-(.62-1.03-1.1 +1.0) = 0.51	
11	4	Inv.	$-\left[\begin{array}{c} \frac{\mathrm{T}}{\mathrm{T_{m}}} \end{array}\right]$	- 3.3	
"	5	Amp.	+ [Tm"]	3.3x2.55 = 8.415	
TR-48		VDFG	$+\left[\begin{array}{c} \frac{K}{K_{m}} \end{array}\right]$	4.5	To multi- plier 1, TR-10
TR-10	6	HG	$-\left[\begin{array}{c} \frac{K}{K_m} \end{array}\right]\left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$	-4.5x1.35/10 =61	From multi- plier 1, TR-10
"	7	Σ	$-\left[\begin{array}{c} \Delta^{C}_{r} \\ \overline{^{C}_{m}} \end{array}\right]$	-(-1.35+.9) = +.45	
"	8	Σ	$-\left[\begin{array}{c} \underline{\Delta}\underline{\mathtt{T}} \\ \overline{\mathtt{T}}_{\underline{\mathtt{m}}} \end{array}\right]$	-(-3.3+3)= + .3	
11	11	Σ	$-\left[\begin{array}{c} \Delta^{C}_{d} \\ \overline{C}_{m} \end{array}\right]$	0	Let there be no change
"	12	Σ	$-\left[\frac{\Delta^{C}_{o}}{C_{m}}\right]$	0	11

TABLE 7.3. (Continued)

Amp No.	FB	Output variables	Static check (volt)	Note s
9	Σ	+ [m* Qcm]	-(+4.5×2.8+.3×8) = -1.5	Let K ₁ =K ₂ = 8
10	Σ	$-\left[\begin{array}{c}Q_{\mathbf{c}}\\Q_{\mathbf{cm}}\end{array}\right]$	-(-1.5-7.5) = +9.03	4
	No. 9	No. 9 Σ	No. $9 \qquad \Sigma \qquad + \left[\frac{m^*}{Q_{cm}} \right]$	No. (volt) $9 \Sigma + \left[\frac{m^*}{Q_{cm}} \right] -(+4.5 \times 2.8 + .3 \times 8) \\ = -1.5$

TABLE 7.4.

Potentiometer assignment sheet for the OAC scheme

(Fig. 7.2)

Computer used	Pot No.	Parameter description	Setting static check	Notes
TR-48	00		0.062 '	eq.(7-31), let F before change
n	01	(a _m T _m T	0.1	B = 0.1
11	02		0.52	eq. (7-31), let F before change
u '·	03	decay constant		by different setting
	05	$\left[\frac{C(0)}{C_{m}}\right]$ / 10	0.135	
11	06	$(c_m/c_m n)$	1.0	ß = 0.1
и	07	æ	0.0五	eq. (7-30), let F before change
n	08	$\left[\frac{T(o)}{T_{m}}\right]/10$	0.33	1 Jozoff Chimip
n	15		0.185	eq. (7-31)
11	16	Ż	0.11	eq. (7-31)
11	17		0.753	eq. (7-22)
11	18	e ₅₀	0.255	section 7.4.3.
TR-10	15	$\left[\begin{array}{c} \frac{F}{F_m} \end{array}\right] / 10$	0.6	
n .	16	*	0.052	eq. (7-30)

TABLE 7.5

Potentiometer assignment sheet for the OAC scheme

(Figs. 7.3, 7.4, 7.5 and 7.6)

Computer	Pot No.	Parameter description	Setting static check	Notes
	418352	Figure 3		
TR-48	25	Optimal P	0.055 x 21	See Appendix 2-7
" .	26	" I	0.055 x 26	
и .	27	" D	0.055 × 27	U
	•	Figure 4	÷	
TR-48	20	*	0.09	eq.(7-24)
11	21		0.3	eq.(7-25)
· 11 ·	04	9	0.09	eq.(7-26)
11	09		0.09	let C be unchanged
"	14		1.0	eq.(7-27)
11	19		1.0	Let C be unchanged
11	22	~ "	0.055 x 21	See Appendix
11	23		0.055 x 22	11
11	24	557	0.055 × 23	"
11	28		0.055 x 24	11
		Figure 5		
TR-48	29	93 15	0.1	due to condition
		Figure 6	:*	
TR-48	30 ~.	9	0.628	eq.(7-41)
11	31.		0.172	eq.(7-41)

TABLE 7.6.

Amplifier assignment sheet for the OAC scheme (Fig. 7.2)

Computer	Amp No.	FB	Output variables	Static check (volt)	Notes
TR-48	06	<u></u>	$+\left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$	+ 1.35	
n.	07	inv.	$-\left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$	- 1.35	
"	21	Σ.	$-\left[\begin{array}{c} \frac{\dot{c}}{\dot{c}_m} \end{array}\right]$	-(.3104261) = 0.342	before any change
TR-10	13	inv.	$+\left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$	+ 1.35	
11	14	inv.	$-\left[\begin{array}{c} \frac{\mathbf{F}}{\mathbf{F}_{\mathbf{m}}} \end{array}\right]$	- 6.0	F before change
u.	15	HG	$-\left[\begin{array}{c} \frac{\mathbf{C}}{\mathbf{C}_{\mathbf{m}}} \end{array}\right]\left[\begin{array}{c} \frac{\mathbf{F}}{\mathbf{F}_{\mathbf{m}}} \end{array}\right]$	(1.35x6.0)/10 = -0.81	11
TR-48	20	ſ	$+\left[\begin{array}{c} \mathbf{T} \\ \mathbf{T}_{\mathbf{m}} \end{array}\right]$	3.3	
ıį	18	inv.	$-\left[\begin{array}{c} \frac{\mathrm{T}}{\mathrm{T_{m}}} \end{array}\right]$	- 3.3	
n .	19	Σ	$-\left[\begin{array}{c} \frac{\hat{T}_{m}}{\hat{T}_{m}} \end{array}\right]$	-(,62-1.03-1.1 +1.0) = 0.51	
н	46	inv.	$+ \left[\begin{array}{c} \frac{\mathbf{T}}{\mathbf{T}_{\mathbf{m}}} \end{array} \right]$	+ 3.3	
11	47	inv.	$-\left[\begin{array}{c} \frac{F}{F_m} \end{array}\right]$	- 6.0	F before change
11	73	HG	$-\left[\begin{array}{c} \underline{\mathbf{T}} \\ \overline{\mathbf{T}}_{\underline{\mathbf{m}}} \end{array}\right] \left[\begin{array}{c} \underline{\mathbf{F}} \\ \overline{\mathbf{F}}_{\underline{\mathbf{m}}} \end{array}\right]$	-(3.3)(+6.0)/10 = 1.98	"
**	27	Amp	$+ \left[\begin{array}{c} \frac{\mathbf{T}}{\mathbf{T_m''}} \end{array} \right]$	3.3x2.55 = 8.415	
"	2.	VDFG	$\left[\begin{array}{c} \frac{K}{K_m} \end{array}\right]$	4.5	

TABLE 7.6. (continued)

TR-48	65 66	Inv.	$-\left[\begin{array}{c} \frac{K}{K_{m}} \end{array}\right]$	- 4.5	
11	66	inv.	Γ α 1		
			$+\left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$	+ 1.35	
"	39	HG	$-\left[\begin{array}{c} \frac{K}{K_{m}} \end{array}\right] \left[\begin{array}{c} \frac{C}{C_{m}} \end{array}\right]$	-(4.5)(1.35)/10 = -0.61	
"	14	<u></u>	$\left[\begin{array}{c} a \\ \overline{a_m} \end{array}\right]$	1.0	before change
	VDFG-1 inv	inv.	$-\left[\begin{array}{c} \frac{a}{a_m} \end{array}\right]$	- 1.0	Inv. in VDFG-1
	VDFG-1	inv.	$+ \left[\begin{array}{c} \frac{K}{K_{\mathbf{m}}} \end{array} \right] \left[\begin{array}{c} \mathbf{C}_{\mathbf{m}} \end{array} \right]$	+ 0.61	Inv.in VDFG-1
11	38	HG *	$-\left[\begin{array}{c} \underline{a} \\ \underline{a}_{\underline{m}} \end{array}\right] \left[\begin{array}{c} \underline{K} \\ \underline{K}_{\underline{m}} \end{array}\right] \left[\begin{array}{c} \underline{C} \\ \underline{C}_{\underline{m}} \end{array}\right]$	- 0.61	
	26	er.	$-\left[\begin{array}{c}Q_{c}\\\overline{Q}_{cm}\end{array}\right]$	-(-1.5-7.5) = +9.03	

TABLE 7.7

Computer	Amp No.	FB	Output variable	Static check (volt)	Notes
			Figure 3		
TR-48	31	Σ.	response error	0	Before operation
u	44	ſ	integral of response error	0	11
11	VDFG-3 inv.	Inv.	$+\left[\begin{array}{cc} \dot{c}_{r} \\ \dot{c}_{m} \end{array}\right]$	- 0.342	Inv. in VDFG-3
u	42	Σ	derivative of response error	0	before operation
u.	VDFG-3 Inv.	Inv.	$-\left[\begin{array}{c} \frac{m^*}{Q_{_{\mathbf{C}m}}} \end{array}\right]$	+ 1.50	Inv. in VDFG-3
11	30	Σ	$+\left[\begin{array}{c} U^* \\ Q_{cm} \end{array}\right]$	- 1.50	
			Figure 4		
TR-48	12	Σ	$-\left[\begin{array}{c} \underline{\Delta}\underline{C} \\ \underline{C}_{\underline{m}} \end{array}\right]$	+ 0.45	
H	13	Σ	$-\left[\begin{array}{c} \underline{\Delta}\underline{\mathbf{T}} \\ \underline{\mathbf{C}}_{\underline{\mathbf{m}}} \end{array}\right]$	+ 0.3	e
**	45	Σ.	$-\left[\frac{\Delta C_{d}}{C_{m}}\right]$	0	Let there be no change
11	74	Σ	$-\left[\frac{\Delta^{C}_{o}}{C_{m}}\right]$	0	"
11	15	Σ	$+\left[\begin{array}{c} \frac{m^*}{Q_{cm}} \end{array}\right]$	- 1.5	Let K ₁ = K ₂ = 8

TABLE 7.7 (continued)

Computer used	Amp No.	FB	Output variable	Static check (volt)	Notes
			Figure 5		
TR-48	33		response error	0	before operation
11	VDFG-2 Inv.	Inv.	- response error	0	Inv. in VDFG-2
11,	74	HG	(response error) ²	0	
n	43	5	Performance response (PR)	0	"
	¥		Figure 6		
	VDFG-4 inv.	Inv.	b	6. 28	Inv. in VDFG-4
	VDFG-4 inv.	Inv.	a.	- 1.72	11

7.6. Operation of the complete simulation

In all operations both for complete simulation and on-line computer control (work in Part II), the results both from theoretical and practical OMRAC operation can be compared almost case by case, figure by figure and curve by curve

7.6.1. Operating possibilities

All of the different kinds of operating conditions of OMRAC can be listed as follows:

- (1) Unmeasurable parameter change: F decrease
- (2) Unmeasurable parameter change: F increase
- (3) Unmeasurable parameter change: a exponential decay

- (4) Unmeasurable combined parameter change: F increase and a exponential decay
- (5) Optimal P of OAC
- (6) Optimal P + I of OAC
- (7) Optimal P + I + D of OAC
- (8) Different initial conditions, C(t) and T(t)
- (9) Different OMR
- (10) Different set point, Cd
- (11) Different inlet concentration, Co.

For more effective planning operations to cover the whole field shown above, the following two rules were obeyed:

- All cases were operated with Optimal P of OAC except
 (6) and (7).
- 2. All cases except (1), (2), (3) and (4) were operated with more effective unmeasurable combined parameter changes:

F : increase ; a : exponential decay (see later).

Following these two rules, ten groups of operation (i.e. (1), (2), (3), (4), (6), (7), (8), (9), (10) and (11) of the above list were used throughout the research work.

Within each group several cases were studied (see next section).

7.6.2. Kinds of figure plotted for each case.

Four kinds of figure for each case were plotted.

- (1) Kind A: Reactor concentration dynamic response, C vs t
- (2) Kind B: Phase plane trajectory, C vs T
- (3) Kind C: Optimal control law generation, U* vs t
- (4) Kind D: Performance response, $\int e^2 dt$ vs t

7.6.3. Types of different operations for each figure

Four different kinds of operation for each figure as shown below was used:

- 1. Unadapted system operation (US) (without control)
- 2. Unadapted Optimal control operation (UOC) (optimal control applied to unadapted system)
- 3. OMR Operation
- 4. OMRAC Operation

7.7. Discussion and analysis of the theoretical results from the complete simulation

7.7.1. Computer OMRAC operation (Table 7.8)

General operating conditions

(1) Initial condition: (In the 1st quadrant from the original steady state, Section 7.1)

$$C(t_0) = 0.135 \text{ mol/litre}; T(t_0) = 33^{\circ}C$$

(2) Final desired concentration

$$C(t_f) = 0.09 \text{ Mol/litre}$$

- (3) OMR : $K_1 = 8$, $K_2 = 8$
- (4) OAC: Optimal P $K_3 = 100, 200, 500 \text{ and } 1000.$

TABLE 7.8.

Computer OMRAC operation for complete simulation

Group	Case	Operating condition	Kind of Plot	Figure
1	1.1	F decrease 10%	A	7.7
		11	. в	7.8
		"	С	7.9
		"	D	A.4.1.
	1.2	F decrease 20%	A	7.10
		11	C	7.11
		"	D	A.4.2.
	1.3	F decrease 30%	A	7.12
		11	c	7.13
		n	D	A.4.3.
	1.4	F decrease 40%	A	7.14
		n	С	7.15
		ונ	D	A.4.4.
2	2.1	F increase 10%	A	7.16
		ш ,	В	7.17
		u .	c ·	7.18
		11	D	A.4.5.
	2.2	F increase 20%	A	7.19
		"	C	7.20
		ii .	D	A.4.6.
3	3.1	a exponential decay 20%	6 A	7.21
		II.	D.	A.4.7.

TABLE 7.8. (continued)

6 (Group 4 (Optimal P+ I + D 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34	Group	Case	Operating condition	Kind of plot	Figure
" D A.4.8. 3.3 a exponential decay 40% A 7.24 " B 7.25 " D A.4.9. 4.1. Combined parameter change: A 7.26 (F increase 10% B 7.27 (a decay 20% C 7.28 " D A.4.10. 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P+ I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34	3	3.2	a exponential decay 30%	A	7.22
3.3 a exponential decay 40% A 7.24 " B 7.25 " D A.4.9. 4.1. Combined parameter change: A 7.26 (F increase 10% B 7.27 (a decay 20% C 7.28 " D A.4.10. 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P + I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34			· ii	c ·	7.23
" D A.4.9. 4 4.1. Combined parameter change: A 7.26 (F increase 10% B 7.27 (a decay 20% C 7.28 " D A.4.10. 5 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P + I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34			, m	D	A.4.8.
" D A.4.9. 4 4.1. Combined parameter change: (F increase 10% (a decay 20% C 7.28 " D A.4.10. 5 5.1 (Group 4 (Optimal P + I K ₃ = 100, & = 0,1,2,3,4. " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 " D A.4.11. 6 (Group 4 (Optimal P + I + D 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34		3.3	a exponential decay 40%	A	7.24
4 4.1. Combined parameter change: (F increase 10% B 7.27 (a decay 20% C 7.28 " D A.4.10. 5 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33			11	В	7.25
(F increase 10%			m.	D	A.4.9.
(a decay 20% C 7.28 " D A.4.10. 5 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P+ I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34	4	4.1.	Combined parameter change:	A	7.26
(a decay 20% C 7.28 " D A.4.10. 5 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P+ I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34				В	7.27
5 5.1 (Group 4 (Optimal P + I) K ₃ = 100, & = 0,1,2,3,4. A 7.29 "				C	7.28
(Optimal P + I K ₃ = 100, & = 0,1,2,3,4. A 7.29 " C 7.30 " D A.4.11. 5.2 K ₃ = 200 & = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P+ I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34			11	D	A.4.10:
" C 7.30 " D A.4.11. 5.2 K ₃ = 200 6 = 0,1,2,3,4,8,15 " B 7.32 " C 7.33 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P+ I + D) 6.1 K = 1, 6 = 0.5,1.0,1.5,2.0 A 7.34	5	5.1		•	
## D A.4.11. 5.2 K ₃ = 200 \$\epsilon = 0,1,2,3,4,8,15			$K_3 = 100, \epsilon = 0,1,2,3,4.$	A	7.29
5.2 K ₃ = 200 £ = 0,1,2,3,4,8,15 A 7.31 " B 7.32 " C 7.33 " D A.4.12. 6 (Group 4 (Optimal P+ I + D 6.1 K = 1, £ = 0.5,1.0,1.5,2.0 A 7.34		39	11	C .	7.30
<pre></pre>		731	ü	D	A.4.11.
" C 7.33 " D A.4.12. (Group 4 (Optimal P+ I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34		5.2	K ₃ = 200		
" C 7.33 " D A.4.12. (Group 4 (Optimal P+ I + D) 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34			- T	A	7.31
Group 4 (Optimal P+ I + D 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34			"	В	7.32
6 (Group 4 (Optimal P+ I + D 6.1 K = 1, & = 0.5,1.0,1.5,2.0 A 7.34			II .	С	7.33
(Optimal P+ I + D 6.1 K = 1, 6 = 0.5,1.0,1.5,2.0 A 7.34		(19)		D	A.4.12.
명하는 문제 전 에 에 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이	6				
" D A.4.13.		6.1	K = 1, & = 0.5,1.0,1.5,2.0	Α .	7.34
			n	D	A.4.13.

TABLE 7.8. (continued)

Group	Case	Operating condition		Kind of plot	Figure
6	6.2	K = 3, € = 0.5,1.0,1.5,2.0		A	7.35
		11		В	7.36
		11		C	7.37
		11		D	A.4.14
7	ı	(Group 4 (Different initial conditi	ons		
	7.1	$(C(t_o) = 0.15 \text{ mol/litre})$)	A	7.38
		$(T(t_0) = 28^{\circ}C$)	В	7.39
		((2nd quadrant))	C	7.40
		()	D	A.4.15
	7.2	$(C(t_0) = 0.07 \text{ mol/litre})$)	A	7.41
		$(T(t_0) = 27^{\circ}C$)	В	7.42
		((3rd quadrant))	С	7.43
		(.)	D	A.4.16
	7.3	$(C(t_0) = 0.06 \text{ mol/litre})$)	A	7.44
	,	$(T(t_0) = 34^{\circ}C$)	В	7.45
*		((4th quadrant))	D	A.4.17
8 .		(Group 4 (Different OMR			
	8.1	(OAR Optimal P K ₃ = 200).	A	7.46
		$((1) K_1 = K_2 = 4)$)	в.	7.47
		$((2) K_1 = K_2 = 8)$)	D	A.4.18
ĸ		$((3) K_1 = K_2 = 15 $)		

TABLE 7.8 (continued)

Group	Case	Operating condition	Kind of plot	Figure
9	9.1	(Group 4 (different set point, C _d	A	7.48
		(OAC Optimal P, K ₃ = 200)	В	7.49
	*	((1) C _d :0.09 — 0.10 mol/).	С	7.50
		(OAC Optimal P, K ₃ = 200) ((1) C _d :0.09 — 0.10 mol/) (litre) ((2) C _d :0.09 — 0.08 mol/) litre	D	A.4.19
10		(Group (Different inlet (concentration		į ·
	10.1	(C as load wariable)	A	7.51
		((1) C ₀ :1.0 — 0.9 mol/) (litre)	В .	7.52
¥		((2) C ₀ :1.0 — 1.1 mol/) (litre)	D	A.4.20
	10.2	(C as parameter)	A	7.53
94	3.	(C _o as parameter) ((1) C _o :1.0 — 0.9 mol/) (litre) ((2) C _o :1.0 — 1.1 mol/) (litre)	В	7.54
		((2) C ₀ :1.0 — 1.1 mol/) litre)	D	A.4.21

7.7.2. An unusual shape of curve was found in Figs. 7.12 and 7.14 for which an exploration is offered in comparison with the curves obtained from other similar conditions. In these figures (cases 1.3 and 1.4) F decrease 30% and 40%, for "US" (Unadapted System) operation, C decreases with an unusual shape. This is due to the large percentage decrease of F, causing a large percentage increase of T and producing a large effect from the non-linear term: $aAe^{-\left(\frac{E}{RT}\right)}$. The same effect occurs with

a large percentage decrease of a in the exponential decay (30% - 40%) where a = e^{-ct} (see Figs. 7.22 and 7.24).

This feature does not arise in OMRAC due to the large increase of $F_{\rm c}$ which forces T to decrease.

7.7.3. For any individual or combination of unmeasurable changed parameters and with the different possible operating conditions from group 1 — group 10), all dynamic response curves and phase-plane trajectories follow a distinct smooth, regular and effective order:

$$(US)_{c} \longrightarrow (UOC)_{c} \longrightarrow \begin{pmatrix} K_{3} = 100 & K_{3} = 200 & \\ K_{3} = 500 & K_{3} = 1000 & \\ \end{pmatrix}_{c} \longrightarrow (OMR)_{c}$$

where -= more offset from OMR.

7.7.4. All optimal law U* and m* also follow a smooth, regular effective order:

OMRAC

$$(K_3=1000-K_3=500-K_3=200-K_3=100)_{U^*}$$
 — $(UOC)_{m^*}$ — $(OMR)_{m^*}$

when K_3 increases, U^*-m^* increases

7.7.5. Performance response: $PR = \int e^2 dt$

shows the effective order:

$$(UOC)_{PR}$$
 OMRAC
 $(K_3=100) K_3=200 K_3=500 K_3=1000$ PR > 0

For the theoretical case:

when
$$C(t) = C_r(t)$$
; $t_0 \le t \le t_f$
then $PR = 0$

7.7.6. From the above facts, the response of OMRAC is always better than UOC and is more effective and approaches OMR more closely as a limit as the weighting factor is increased.

- 7.7.7. From all dynamic response curves and phase plane trajectories, OMRAC displays excellent asmptotic stability.
- 7.7.8. The adaptation of OMRAC seems to have no limitation for any operating conditions shown in 7.7.1. The only limitation is the constraint of the optimal control law U*, which corresponds to the control valve capacity for cooling water flowrate.
- 7.7.9. Optimal P + I and Optimal P + I + D of OMRAC can produce greater improvement tham Optimal P only, and Optimal PID has the same general properties as the conventional PID controller (see Groups 5 and 6).
- 7.7.10. All of the above discussion is based on a qualitative analysis of OMRAC. For the quantitative analysis of OMRAC, a new term "OPTIMAL ADAPTIVITY" is introduced and discussed in detail in Chapter 11, Part II.
- 7.7.11. From all of the above discussion and analysis the theoretical development of OMRAC has been positively supported and proved, and the further work of on-line hybrid computer operation in combination with a partially simulated CSTR is studied and shown in Part II.

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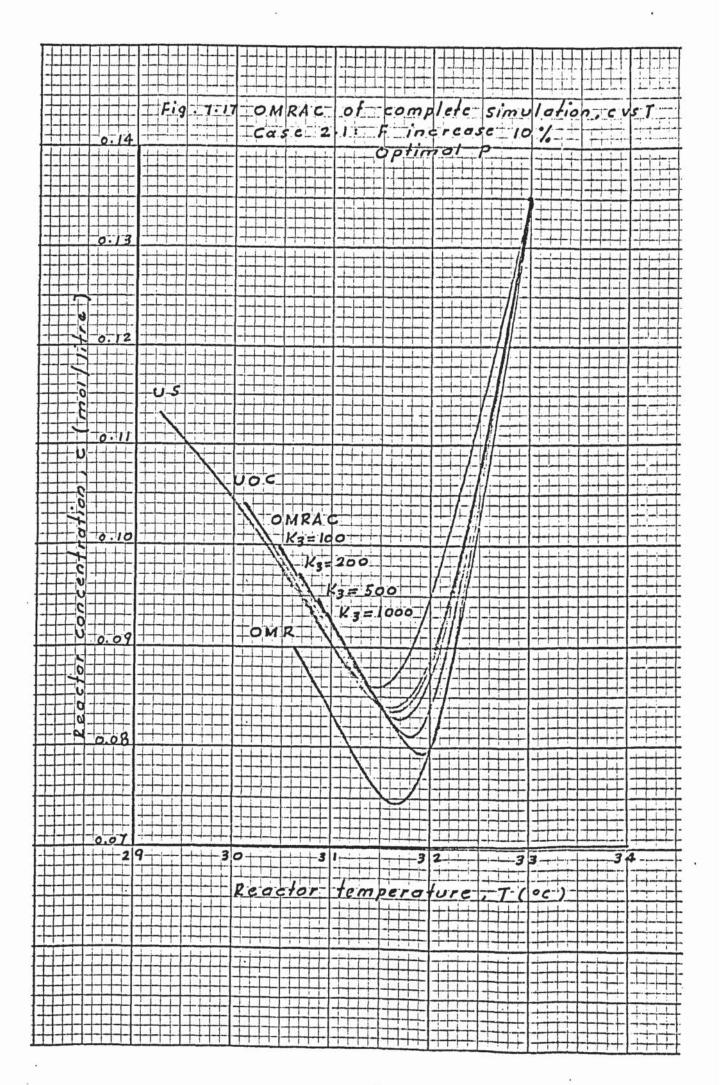
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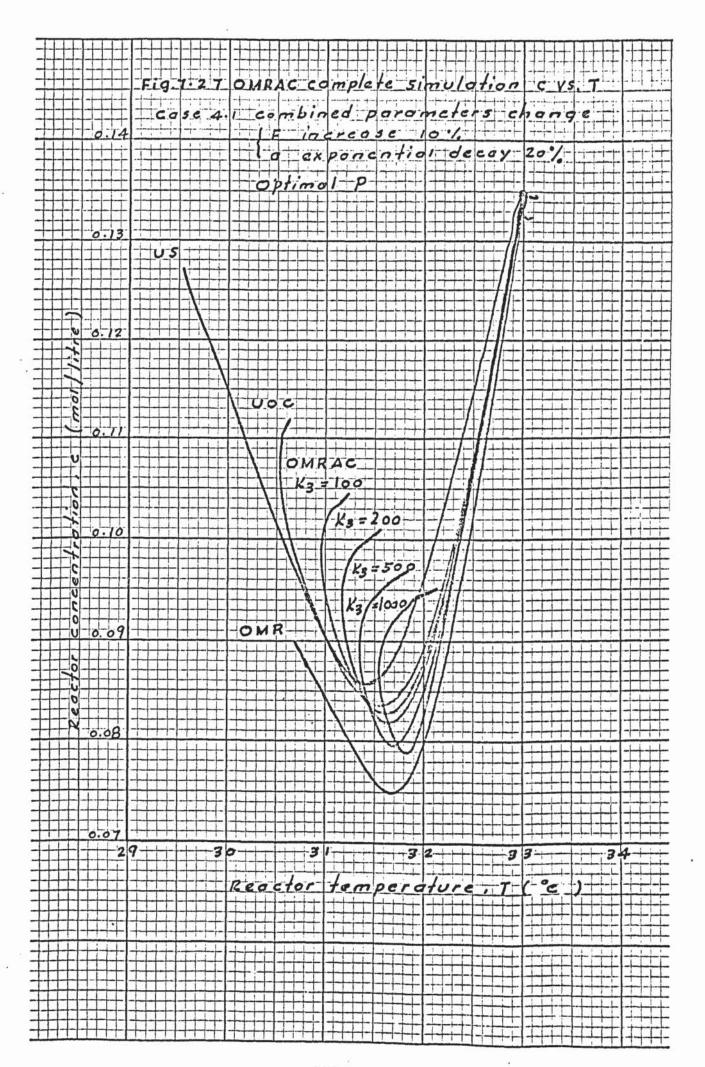
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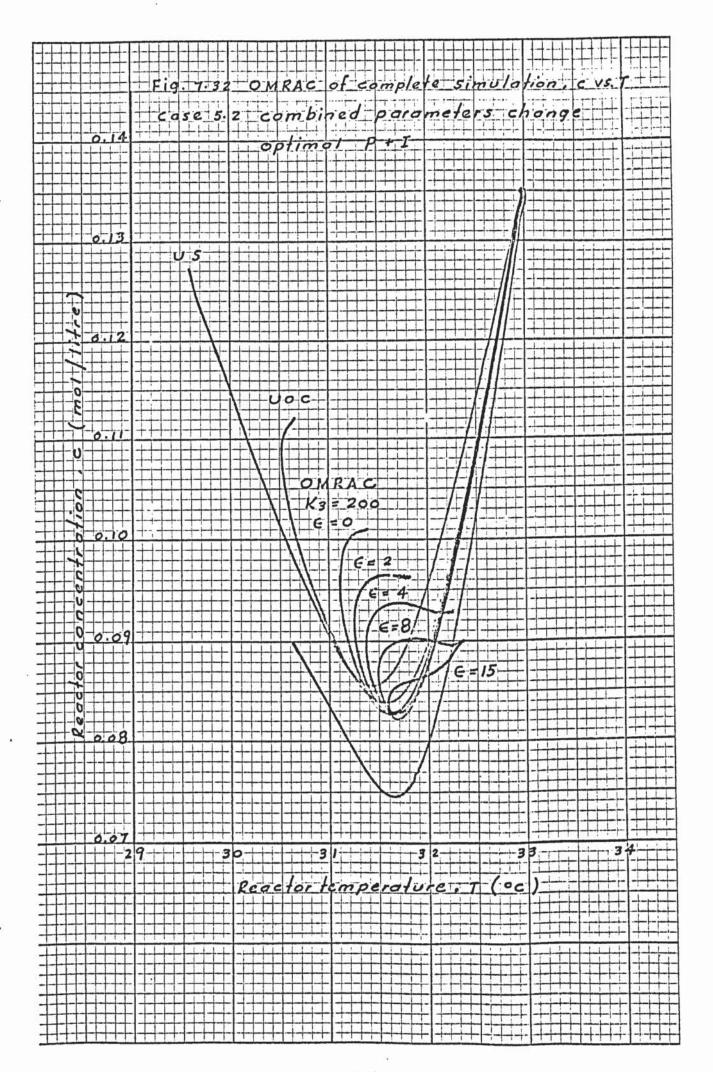


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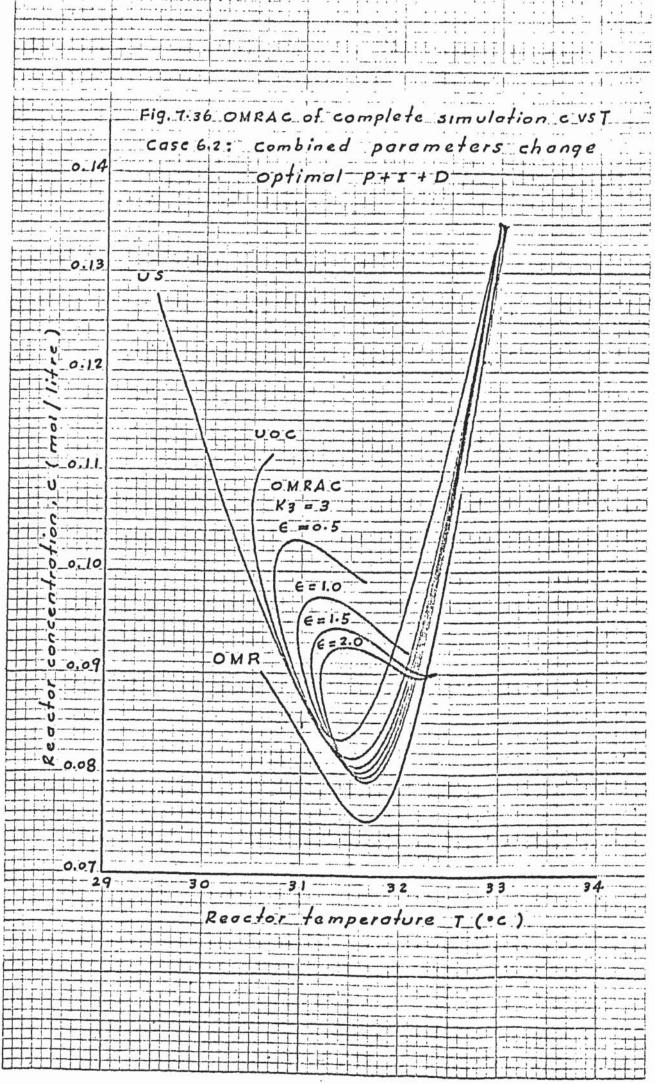
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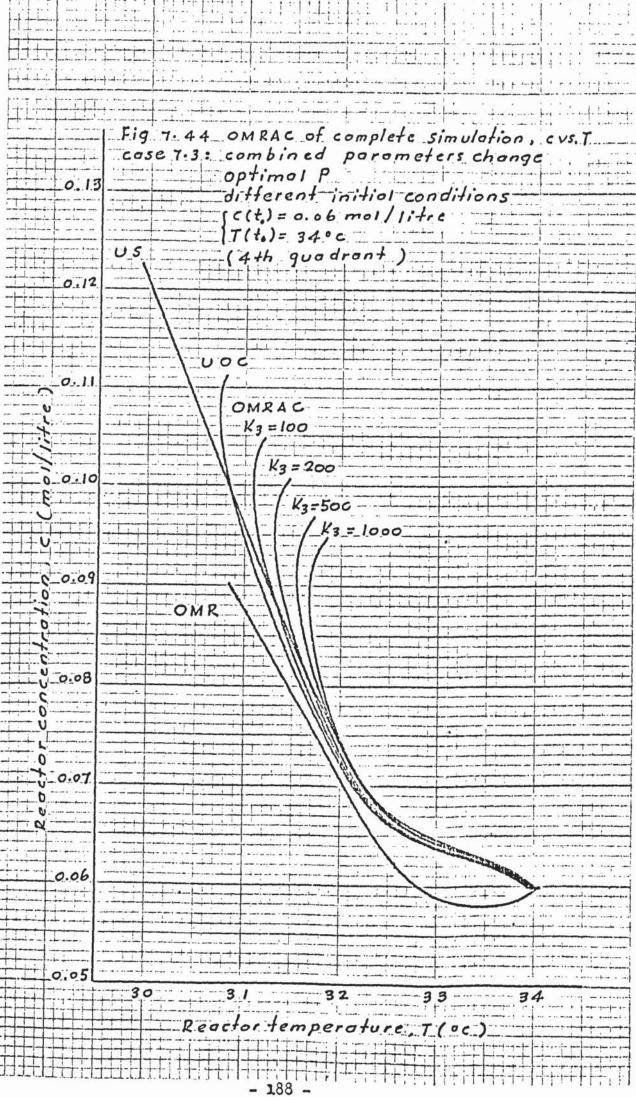
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3 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3	34
3 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3	34
30-31-32-33	34

PART II

ON-LINE COMPUTER CONTROL WORK

(Chapter 8 to Chapter 11)

CHAPTER 8

ON-LINE COMPUTER OMRAC SYSTEM

8.1. Modified experimental apparatus

8.1.1. Functional and modified apparatus diagram

The overall functional diagram for operating the on-line hybrid computer OMRAC system is shown in Fig. 8.1.

The material balance equation (7-1) and part of the energy balance equation (7-2) of a CSTR are simulated directly on the hybrid computer. Heat is generated in the reactor by means of immersion heaters at a rate controlled by a position servomechanism technique (81); this was developed by Buxton (80). For on-line computer OMRAC operation, additional and modified equipment and instruments were necessary. Using the techniques of complete simulation (Chapter 7), the optimal control law generated by the OMRAC scheme by the computer is transmitted through the interface system to operate the control valve directly, and the cooling water flowrate F_c is adjusted for adaptation to the unmeasurable parameter changes and other disturbances.

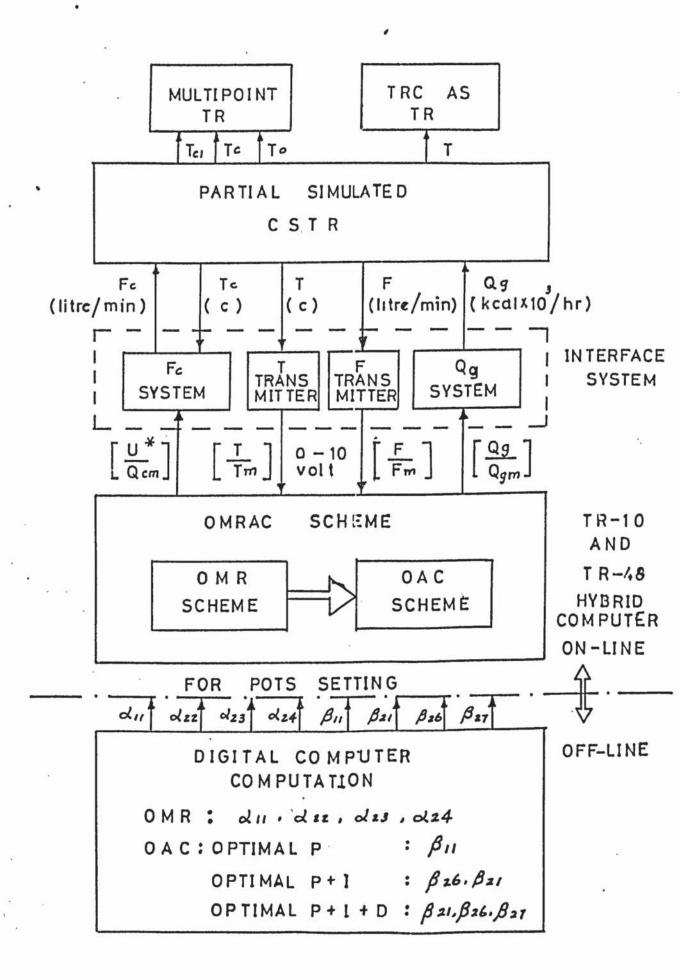
The modified experimental apparatus designed for the on-line computer OMRAC system is shown on Fig. 8.2 and three corresponding photographs show the actual operating system.

8.1.2. Modification and calibration of experimental apparatus

1. F_c system

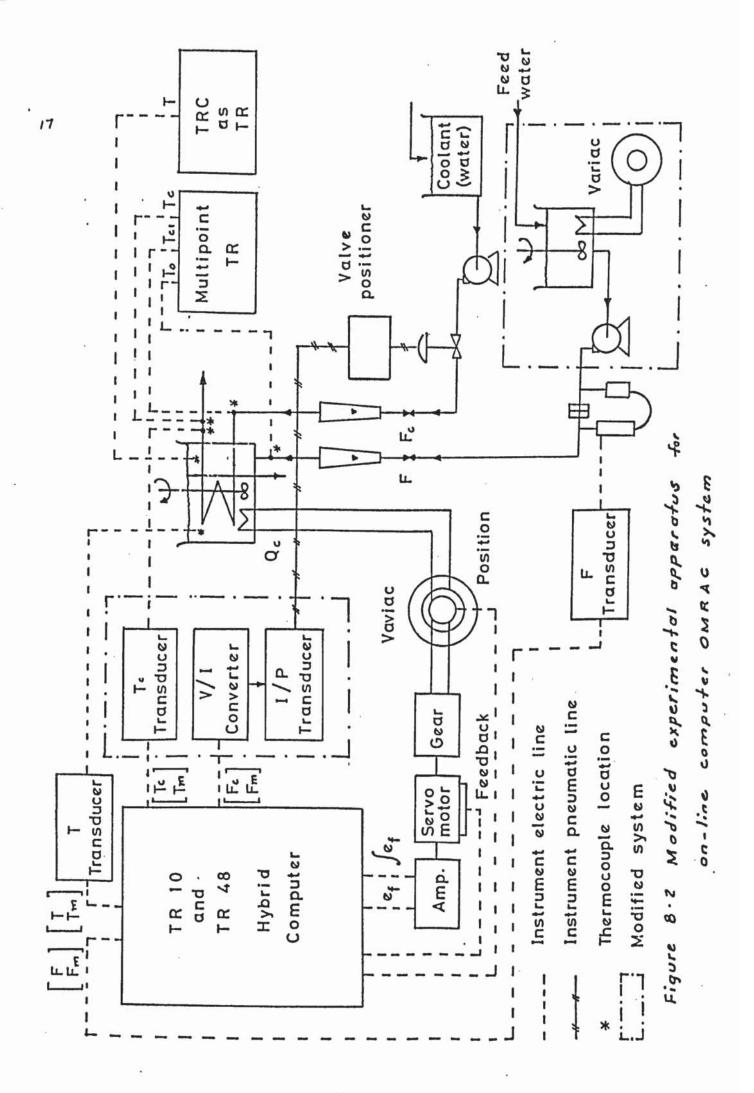
$$F_c$$
 is transferred from $\left[\frac{Q_c}{Q_{cm}}\right]$ or $\left[\frac{F_c}{Q_{cm}}\right]$ (computer

side, 0 to 10 volt) to F_c (process side, 0 to 10



16

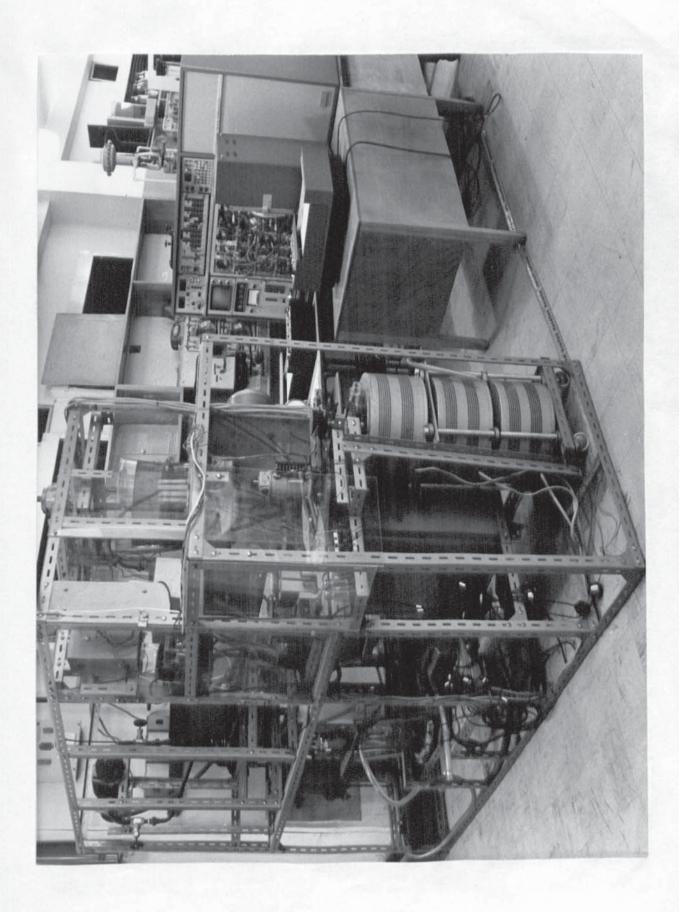
Figure 8.1 Functional diagram of on-line computer OMRAC system



- 201 -

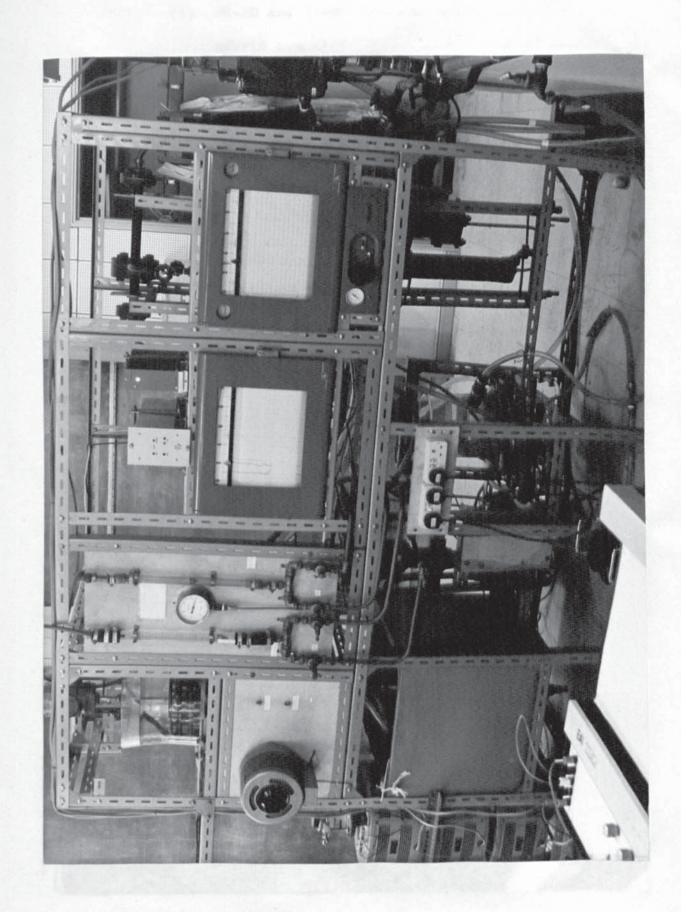
ON-LINE COMPUTER OPERATING EQUIPMENT

(1) Overall system

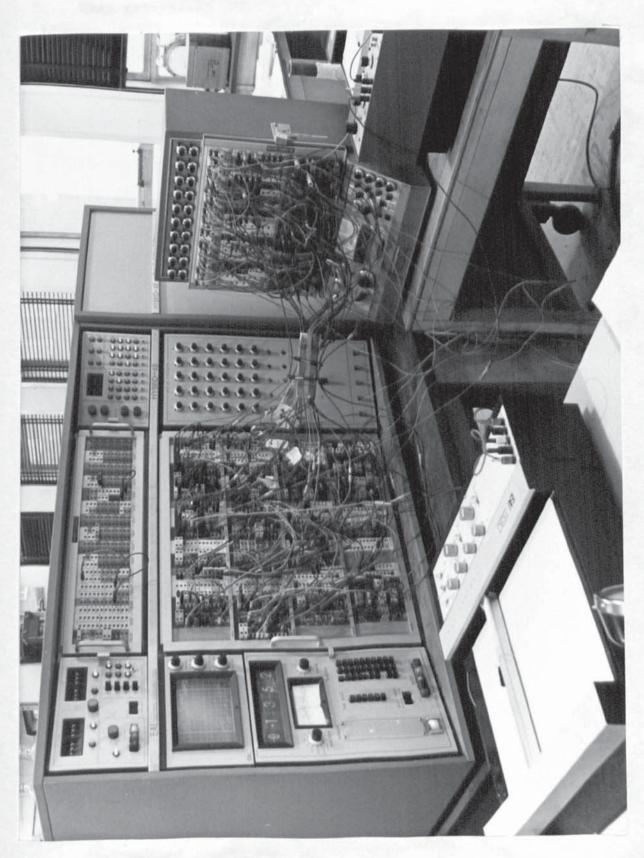


ON-LINE COMPUTER OPERATING EQUIPMENT

(2) Modified partial simulation equipment



(3) TR-10 and TR-48 analogue and hybrid computer



litre/min) and as an important major interface aspect of on-line computer OMRAC will be discussed in detail in the next Section (8.2).

2. Heat generation system (Q_g)

 Q_g is transferred from $\left[\frac{Q_g}{Q_{gm}}\right]$ (computer side, 0-10 volt) to actual Q_g (process side, 0-10 Kcal x $10^3/h$) through the position servomechanism and immersion heaters. The calibration of the existing Q_g system is given in detail in the next section (8.2).

From the existing heat generation system, the following items were modified:

- (1) A new field-controlled dc servomotor with generator was installed, (Servo and Electronic Sales Ltd., Type: 67883), since the existing motor was not in good condition.
- (2) Two gears between the servomotor and variac were replaced to double the gear ratio:

original : 23 : 23, i.e. 1 : 1

new : 38:18, i.e. 2.1:1

and hence to double the available torque to position the variac more smoothly.

- (3) The switch and fuse location of the position servomechanism system was changed to prevent overloading and damage to the motor (Fig. 8.3).
- Rendering of inlet feed temperature independent of seasonal variations.

The inlet feed water temperature is significantly influenced during cold weather and causes the control

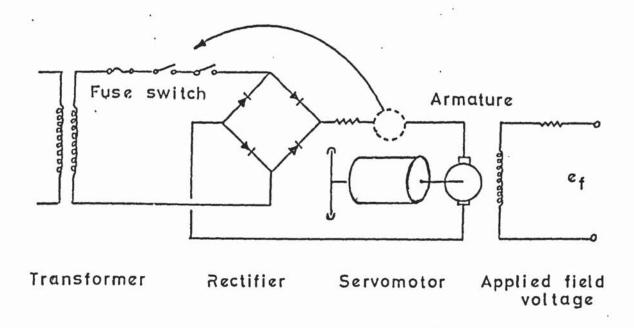
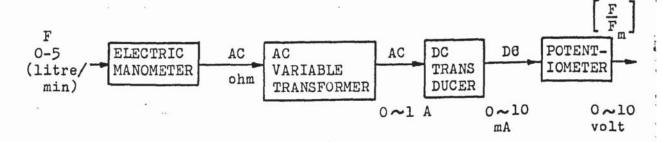


Figure 8.3 change switch and fuse location on field controlled servomotor

. :

valve to operate near to the closed position (rotameter reading of F_c off lower end of scale) at steady state. Hence a small water tank with adjustable immersion heater and pump were added (Fig. 8.2 and photograph) so that the temperature of the inlet feed water could be increased to produce a suitable operating range of coding water flowrate F_c through the control valve at steady state.

- 4. Calibration of the original two rotameters the one for inlet feed flowrate F, and the other for cooling water flowrate F_c (see Appendix, Tables A.5.1. and 5.2. and Figs. A.5.1. and A.5.2.).
- 5. Calibration of the original flow transmitter: (model: Elliott electrical manometer, 438-77).



(See Appendix, Table A.5.3. and Fig. A.5.3.)

6. Repair and calibration of all original thermocouples:
Material:

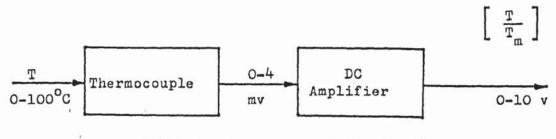
Nickel chromium Alloy T1 (+) 0.0148" diameter

Nickel Aluminium Alloy T2 (-) 0.0148" diameter

Number of thermocouples:

- (1) Feed water temperature, T_c to TR
- (2) Cooling water inlet temperature, Tol to TR
- (3) Cooling water outlet temperature, Tc to TR
- (4) Reactor temperature, T to TRC used as TR (Appendix, Table A.5.4 and Fig. A.5.4).

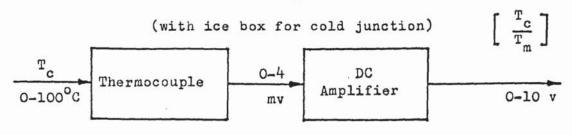
- 7. Calibration of temperature transmitters.
 - (1) Existing Reactor temperature transmitter
 (Model: Elliott TDC 21)



(with ice box for cold junction)

(2) New cooling water outlet temperature transmitter

(Model: Elliott M45/mv)



(Appendix, Table A.5.5 and Fig.A.5.5)

8.2. Interface system design

From Figs. 8.1 and 8.2 in Section 1, the major interface transfers for on-line computer OMRAC operation are F_c and Q_g . Q_g is specially used for the partially simulated CSTR, and F_c is used to transfer any complicated optimal control law (adapted or unadapted) to pneumatic pressure to operate the control value and adjust F_c directly. So F_c is the more important major interface system for any on-line computer control. The requirement of interface system design like for any industrial transmitters or transducers, is that the terminal relation between input (computer side) and output (process side) must be extremely linear. To meet this requirement the interface system was designed in detail as follows:

8.2.1. F_c system

The detailed block and functional diagram of the F_c system was designed and is shown in Fig. 8.4.

Fig. 8.4. clearly shows that the major purpose of the added VDFG is to produce an excellent linear relation between $\left[\begin{array}{c} F_{\text{c}} \\ \overline{F}_{\text{m}} \end{array}\right]$ and F_{c} by suitably programming of the VDFG (see 8.2.1. (5)).

The components of the F_c system are discussed below:

1. Voltage to current (V/I) converter (Lee Dickens Model C5740)

input : 0 to 10 volts

output: 0 to 20 ma

The calibration curve is shown in Appendix, Table A.5.6. and Fig. A.5.6.

2. Current to pneumatic pressure (I/P) transducer (Honeywell model 3120/01)

input : O to 20 ma

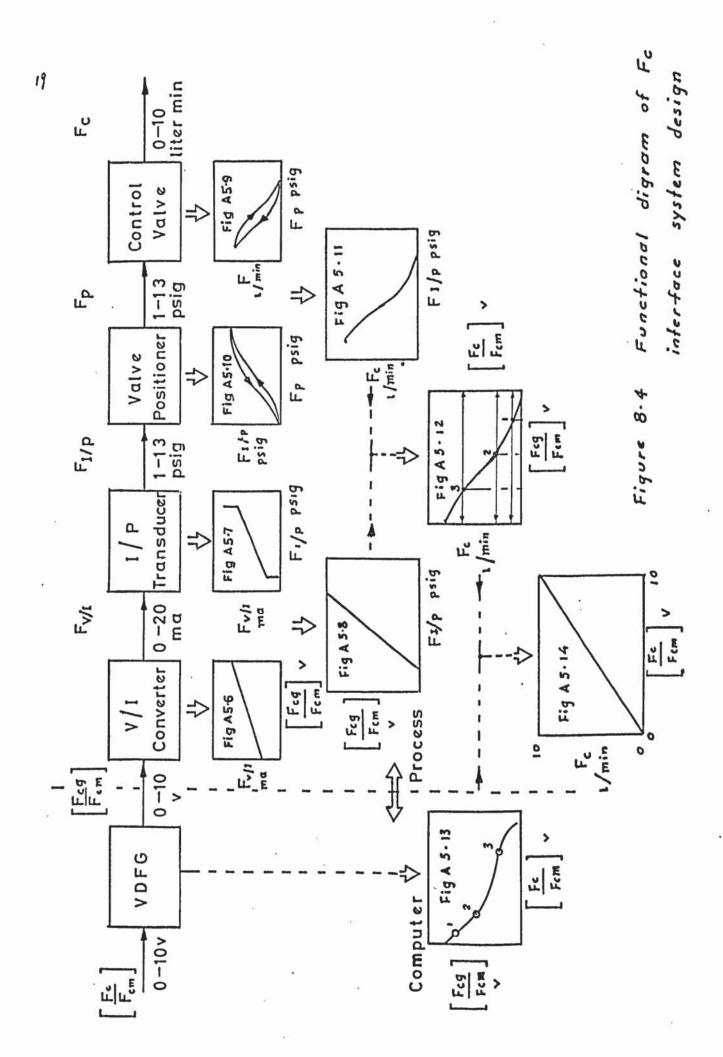
output : 3 to 15 psig or 1 - 13 psig

The calibration is shown in Appendix, Table A.5.7. and Fig.A.5.7. and the combined V/I and I/P calibration curve is shown in Appendix, Table A.5.8. and Fig.A.5.8.

3. Control valve and valve positioner.

The major advantages of the valve positioner are:

(1) to produce more power which can decrease or eliminate the control valve hysterisis effect.



(2) to produce quick response which can decrease or eliminate the control valve time lag.

Without the valve positioner, the characteristic of the control valve in response to applied pneumatic pressure always possessed a hysterisis effect as shown in Appendix, Table A.5.9. and Fig. A.5.9.

When the valve positioner was added, the calibration curve of the positioner (Appendix, Table A.5.10 and Fig.A.5.10) can just compensate for the hysterisis of the control valve and the combined effect is shown in Appendix, Table A.5.11 and Fig. A.5.11, in which the hysterisis effect is almost eliminated.

4. Resultant function.

On combination of all components: V/I converter, I/R transducer, valve positioner and control valve, the resultant function between $\left[\frac{F_{cg}}{F_{cm}}\right]$ (computer side) and

F_c (process side) is a non-linear curve (Appendix, Table A.5.12 and Fig. A.5.12).

5. VDFG programming.

Using the resultant function, a compensation curve of F_C interface system on VDFG can be plotted as shown in Appendix Fig.A.5.13., and this curve is programmed in detail on the TR-48 VDFG-3 (Appendix Fig. A.3.2.).

Thus for the final F_c system, the signal from the computer transmitted through the generated VDFG and then a series function of monitoring instruments, gave an excellent

linear relation between $\left[\frac{F_c}{F_{cm}}\right]$ and the F_c obtained is shown in Appendix Table A.5.13 and Fig.A.5.14.

8.2.2. Q system

The detailed block and functional diagram for Q_g is shown on Fig. 8.5, and the components are discussed below:

(1) The calibration of variac position including servo-mechanism components, amplifier, servomotor and gears, $\text{or} \left[\frac{Q_{gg}}{Q_{gm}} \right] \text{ from computer versus variac reading (VR),}$

is shown in Appendix Table A.5.14 and Fig. A.5.15.

(2) The calibration of immersion heater, or VR versus Q_g is shown in Appendix Table A.5.15 and Fig.A.5.16.
Q_g is calculated from experimental data while F and ΔT from the following:

$$Q_{g} = V (-\Delta H) KC$$

$$= \rho_{c} C_{pc} F_{c} (\Delta T_{c}) + \rho C_{p} F (\Delta T) \qquad (8-1)$$

F = 0 for the rest:

$$Q_{g} = F \Delta T \left(\frac{\text{Kcal}}{\text{min}}\right)$$

$$= 0.06 F \Delta T \left(\text{Kcal} \times 10^{3}/\text{h}\right) \qquad (8-2)$$

It is seen in Fig.A.5.17 that only a small hysterisis effect remained.

(3) The calibration of the combined variac position and immersion heater or $\left[\frac{Q_{gg}}{Q_{gm}}\right]$ versus Q_g is shown in Appendix Fig. A.5.17.

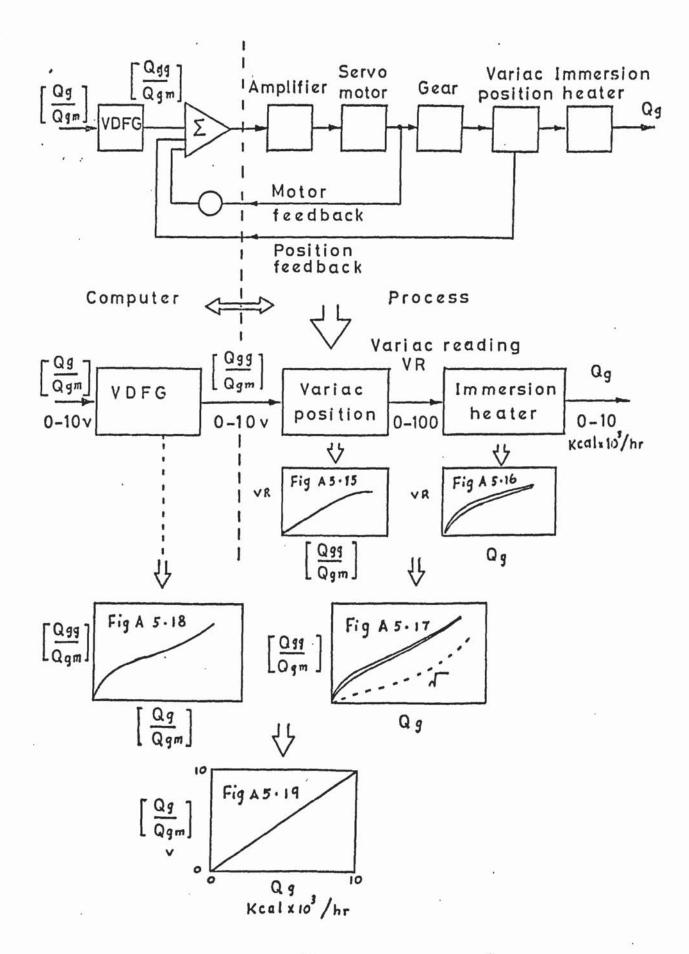


Figure 8.5 Functional digram of Qg interface system design

From Fig.A.5.17 the resultant response curve is apparently non-linear. Buxton suggested that using a square root, or the output from $\sqrt{\left[Q_{gg}/Q_{gm}\right]}$ would give an approximately linear relationship with Q_{g} (see Buxton's Ph.D.Thesis, Fig.A.11, p.316, and this curve is reproduced and shown in Fig.A.4.18). However, from the experimental data, $\sqrt{\left[Q_{gg}/Q_{gm}\right]}$ is also non-linear (Fig.A.5.17). Hence using the technique shown in the above section, an additional VDFG was used instead of the square root function

(4) VDFG programming

From the average value of two small hysterises calibration curves from Fig.A.5.16, a new compensated function was generated on a VDFG as shown in Appendix Fig.A.5.18 and was programmed on the TR-10 DFG (Appendix Fig.A.3.3.)

For the final Q_g , the signal from the computer was transmitted through the DFG and a series of monitoring equipment and an excellent linear relation between $\left[Q_g/Q_{gm}\right]$ and Q_g was obtained (Appendix Table A.5.16 and Fig.A.5.19)

8.3. Programming the computer.

8.3.1. OMR scheme computer programming

The computer diagram of the OMR scheme is as shown in Chapter 7, Complete Simulation (7.4.1. and Fig.7.1.) The only difference is that the time scale factor β is equal to

$$\tau = \beta t = t \tag{8-3}$$

Thus the computer time is equal to the process real, time and the same as in the OAC scheme.

8.3.2. OAC scheme computer programming

The computer diagram of the OAC scheme is shown in Fig. 8.6. Several important components and parts shown in Fig. 8.6 are noted below:

- 1. The computer diagram of optimal PID generation is as in Chapter 7: Complete Simulation (7.4.2. and Fig.7.3), and the only differences are:
 - (i) no constraint circuit since the control valve can be treated as a limiter between minimum and maximum flowrate of F_c (see 4.4).
 - (ii) $\left[\frac{U^*}{Q_{cm}}\right]$ from Amp.30 is directly connected to F_c program (Fig.8.8).
- 2. The computer diagram of the optimal control law generated for the unadapted system is the same as in Chapter 7: Complete Simulation (7.4.2 and Fig. 7.4) and the only differences are:
 - (i) $\left[\frac{T}{T_m}\right]$ signal is connected to the reactor temperature transmitter
 - (ii) $\left[\frac{m^*}{Q_{cm}^*}\right]$ from Amp.15 is directly connected to F_c program (Fig.8.8).
- 3. $\left[\frac{T}{T_m}\right]$ signal is connected to the reactor temperature transmitter (8.1.2 (7)).
- 4. $\left[\frac{F}{F_m}\right]$ signal is connected to the feed flow transmitter (8.1.2. (5))

- 5. The computer programming of the Q interface system is discussed in section 8.3.3.
- 6. The computer programming of the F_c interface system is discussed in section 8.3.4.

8.3.3. Q system computer programming

From the functional diagram (Fig. 8.5), the computer programming of the Q_g system is shown in Fig. 8.7.

The relation between $\left[\frac{a}{a_m}\right] \left[\frac{K}{K_m}\right] \left[\frac{C}{C_m}\right]$ and $\left[\frac{Q_g}{Q_{gm}}\right]$

is calculated below

$$Q_{g} = (-\Delta H) \ V \ a \ K \ C$$

$$= (\frac{\text{cal}}{\text{mol}}) \ (\text{litre}) \ (\frac{1}{\text{sec}}) \ (\frac{\text{mol}}{\text{litre}}) = (\frac{\text{cal}}{\text{sec}})$$

$$= \frac{3600}{1000 \ x \ 1000} \ (\frac{\text{Kcal} \ x \ 10^{3}}{\text{h}})$$
or
$$\left[\frac{Q_{g}}{Q_{gm}}\right] = (\frac{3600}{1000 \ x \ 1000}) \frac{(-\Delta H)(V)(^{a}_{m})(^{K}_{m})(^{C}_{m})}{Q_{gm}} \left[\frac{a}{a_{m}}\right] \left[\frac{K}{K_{m}}\right] \left[\frac{C}{C_{m}}\right]$$

$$= (\frac{3600}{1000 \ x \ 1000}) \frac{(18511)(16)(1)(0.1)(1.0)}{10} \left[\frac{a}{a_{m}}\right] \left[\frac{K}{K_{m}}\right] \left[\frac{C}{C_{m}}\right]$$

$$\therefore \left[\frac{Q_{g}}{Q_{gm}}\right] = 10.66 \left[\frac{a}{a_{m}}\right] \left[\frac{K}{K_{m}}\right] \left[\frac{C}{C_{m}}\right]$$
(8-4)

The values of $(0.1066) \times (10) \times (10)$ are the settings on Pot 00 and Amp. 18 and 19 shown in Fig.8.7.

In Fig. 8.7, sw-l is used as the switch to solve for the initial value for on-line operation discussed in detail in Chapter 9 (9.4)

In Fig. 8.7, for Buxton's original design of position servomechanism, both e_f and $\int e_f dt$ are used as input to

amplifier and servomotor as applied field voltage. Since the change to a new servomotor and gear ratio (see 8.1.2.) both inputs (e_f) and $(e_f + \int e_f dt)$ can produce the same smooth and sensitive operation, and so only e_f was used as the input to simplify the on-line operation.

8.3.4. Fc system computer programming

From the functional diagram (Fig. 8.6), the computer programming of the F_c system is shown in Fig. 8.8.

In Fig. 8.8, three switches are operated according to the following rules:

	¥ - *	sw-2	5-wa	sw-4
1.	Operation for adjusted			
٠.	initial condition	R	L	R or L
	(before start)			
2	Unadapted system			
	operation (US)	L	L	R or L
3.	Unadapted Optimal			
	control operation	L	R	L
	(UOC)			
4.	Optimal adaptive			
(*)	control operation	L	R	R
	(OMRAC)			

where R = right: L = left

The relation between
$$\left[\frac{Q_c}{Q_{cm}}\right]$$
 or $\left[\frac{U^*}{Q_{cm}}\right]$ and $\left[\frac{m^*}{Q_{cm}}\right]$ and $\left[\frac{F_c}{Q_{cm}}\right]$ is calculated below:

$$Q_{c} = \rho_{c} C_{pc} F_{c} \Delta T_{c}$$

$$= (\frac{gm}{cm^{3}})(\frac{cal}{gm \times C})(\frac{litre}{min})(\frac{1000 cm^{3}}{litre})(^{\circ}C)$$

$$= 1000 (\frac{cal}{min}) = 1 (\frac{Kcal}{min})$$
(8-5)

or
$$\left[\frac{Q_{c}}{Q_{cm}}\right] = \frac{(F_{cm})(T_{m})}{(Q_{cm})} \left[\frac{F_{e}}{F_{cm}}\right] \left[\frac{\Delta T_{c}}{T_{m}}\right]$$

$$= \frac{(10)(100)}{100} \left[\frac{F_{c}}{F_{cm}}\right] \left[\frac{\Delta T_{c}}{T_{m}}\right]$$
(8-6)

$$\cdot \cdot \left[\frac{Q_{c}}{Q_{cm}} \right] = 10 \left[\frac{F_{c}}{F_{cm}} \right] \left[\frac{\Delta T_{c}}{T_{m}} \right]$$
 (8-6)

or
$$\left[\frac{F_{c}}{F_{cm}}\right] = \frac{0.1 \left[\frac{Q_{c}}{Q_{cm}}\right]}{\left[\frac{\Delta^{T}_{c}}{T_{m}}\right]}$$
 (8-7)

$$\left[\begin{array}{c} \frac{Q_{_{\mathbf{C}}}}{Q_{_{\mathbf{C}m}}} \end{array} \right] \ = \ \left[\begin{array}{c} \frac{Q_{_{\mathbf{C}s}}}{Q_{_{\mathbf{C}m}}} \end{array} \right] \ + \left[\begin{array}{c} \frac{U^*}{Q_{_{\mathbf{C}m}}} \end{array} \right]$$

$$\cdot \cdot \left[\frac{F_{c}}{F_{cm}} \right] = \frac{0.1 \left[\frac{Q_{cs}}{Q_{cm}} \right]}{\left[\frac{\Delta T_{c}}{T_{m}} \right]} + \frac{0.1 \left[\frac{U^{*}}{Q_{cm}} \right]}{\left[\frac{\Delta T_{c}}{T_{m}} \right]}$$
(8-8)

or
$$\left[\frac{F_c}{F_{cm}}\right] = \left[\frac{F_{cs}}{F_{cm}}\right]_{final} + \frac{0.1 \left[\frac{U^*}{Q_{cm}}\right]}{\left[\frac{\Delta T_c}{T_m}\right]}$$
 (8-9)

when unadapted optimal control is applied, then

$$\left[\frac{F_{c}}{F_{cm}}\right] = \left[\frac{F_{cs}}{F_{cm}}\right]_{final} + \frac{6.1 \left[\frac{m^*}{Q_{cm}}\right]}{\left[\frac{\Delta T_{c}}{T_{m}}\right]}$$
(8-10)

where

 $\begin{bmatrix} \frac{F_{cs}}{F_{cm}} \end{bmatrix}_{final} = \text{actual cooling water flowrate at}$ the final steady state of on-line computer operation and converted into volts. }

In the original design, equation (8-7) was used for programming the computer, but the actual accurate value of $\left[\frac{Q_{cs}}{Q_{cm}}\right]_{final}$ of the on-line computer operation was very difficult to obtain, so finally equations (8-9) and (8-10) were developed and chosen for programming the computer (Fig. 8.8) by introduction of an iterative operation technique; the accurate value of $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ is obtained and discussed in detail in Chapter 9 (9.5 and 9.6).

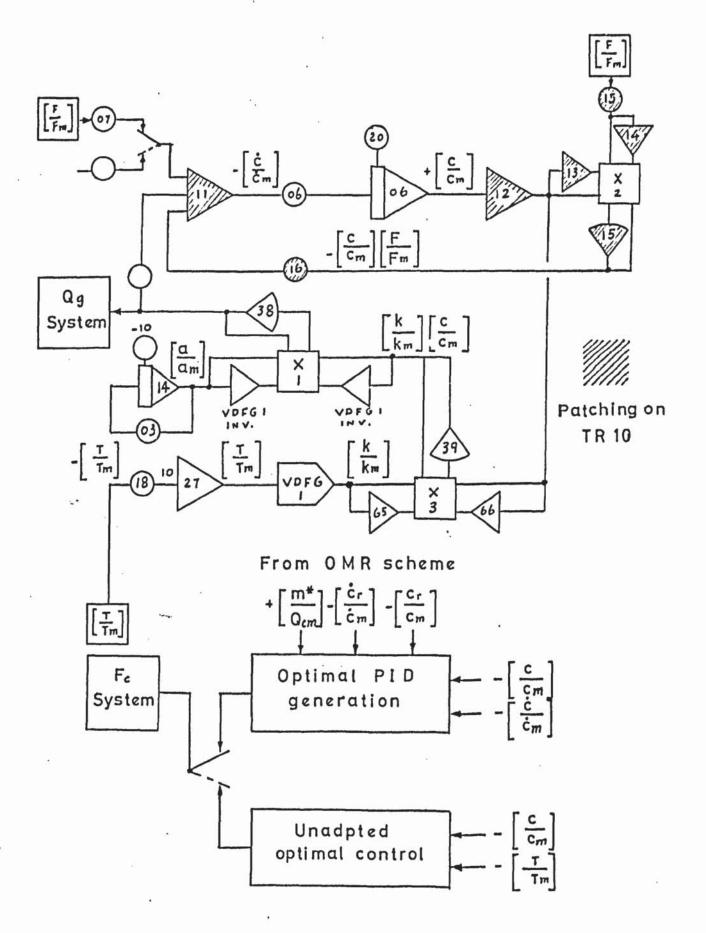
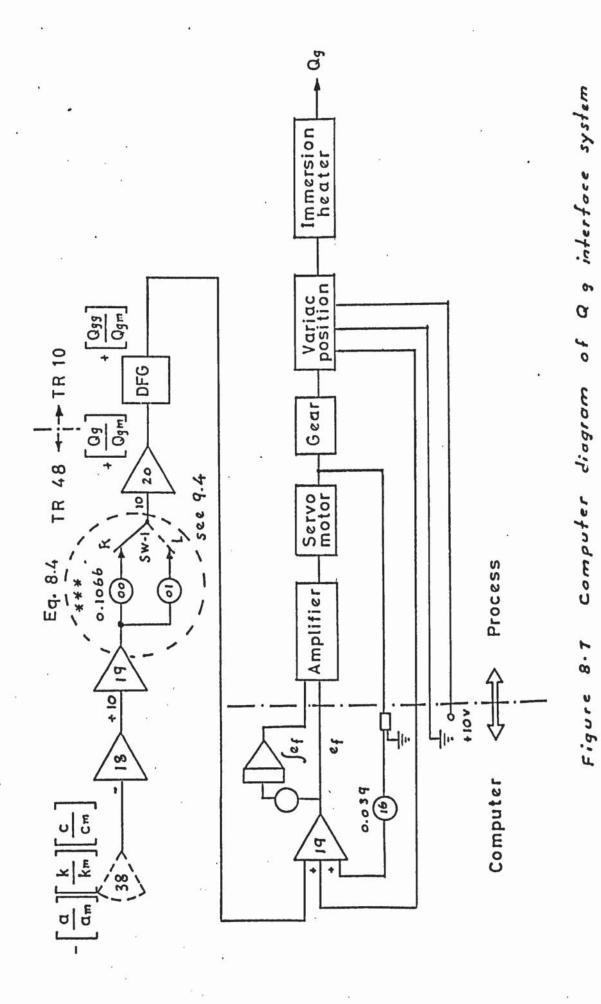


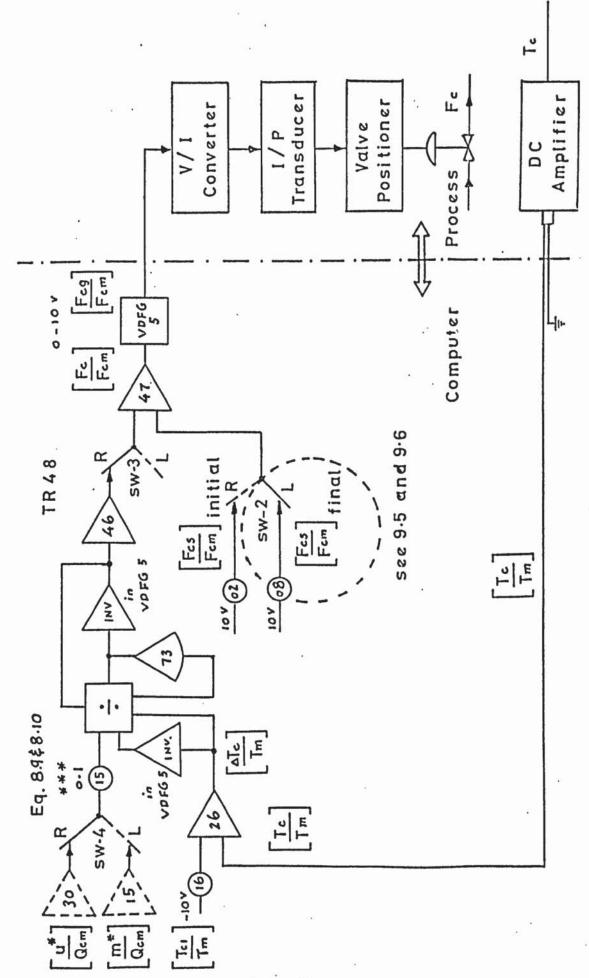
Figure 8.6 Computer diagram of on-line

OAC scheme (on TR-48)

-217-



- 218 -



219 -

Computer diagram of Fc interface system Figure 8.8

CHAPTER 9

COMMISSIONING OF ON-LINE COMPUTER OPERATION

9.1. Test Run

Before successful operation of the on-line computer OMRAC, a continuous test run of on-line operation was considered vital. The purpose was to test the overall performance of the on-line system and to find successful operating procedures and techniques to produce reliable and reproducible on-line computer operation for OMRAC.

From previous work including complete simulation shown in Chapter 7 and interface design and on-line computer programming shown in Chapter 8, a rigid foundation for on-line operation has been established. But from a long duration test run, several operating difficulties were found and are listed below:

- 1. The joining of two computers for real time on-line operation (discussed in 9.2)
- Smooth plot of fluctuating reactor temperature (discussed in 9.3).
- 3. Effect on initial temperature setting on partially simulated CSTR (discussed in 9.4).
- 4. Determination of $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ on partially simulated CSTR (discussed in 9.5).
- 5. Effect if F step change on partially simulatedCSTR (discussed in 9.6).

It should be pointed out that the difficulties (2), (3), (4) and (5) shown above exist and are amplified because of the very narrow operating ranges on the X-Y plotter used in this whole research work compared with a wide operating range used in Buxton's

Ph.D. Thesis (80) which were:

Temperature 0 - 40 °C or 10.0 deg C/inchConcentration $0 - 4 \frac{\text{mol}}{\text{litre}}$ or $0.05 \frac{\text{mol}}{\text{litre}}$ /inch

In the present research the operating ranges on the X-Y plotter were:

Temperature $30 - 34^{\circ}C$ or 1.0 deg C/inch Concentration $0.06 - 0.14 \frac{\text{mol}}{\text{litre}}$ or $0.01 \frac{\text{mol}}{\text{litre}}$ /inch

Since the operating range in this research decreased by a factor of 10 in temperature and 5 in concentration, then the sensitivity was also increased tenfold in temperature and fivefold in concentration. That means that the overall sensitivity in this research work is 50 times that of Buston's.

In general, a more narrow range of operation can produce more sensitive and accurate response results but also produces many more operating difficulties than wide range operation.

All difficulties shown above are discussed and details of their solution given in the following sections of this chapter.

9.2. Two computers joined for on-line operation.

The difficulties of analogue computer operation increase in the following order:

In the previous complete simulation work (Chapter 7) the programming of OMR and OAC was patched on the TR-10 and TR-48

respectively (Figs. 7.1 and 7.2). Usually the dynamic response of OMR and OAC with constant parameters was approximately the same (operating time approximately 60 sec). This gives a useful dynamic check before each operation. But for on-line slow operation (operating time approximately 600 sec.) the dynamic response of the OMR patched on the TR-10 was still kept approximately the same, but the dynamic response of the OAC patched on the TR-48 was apparently changed. This may be due to the performance of each computer.

After the main part of OAC programming was re-patched on the TR-10 (Fig. 8.6) then this difficulty was overcome.

For on-line operation with joined TR-10 and TR-48 computers, the following simple rules for patching and checking were followed:

- (1) The performance of each component of both computers was checked.
- (2) All integrators were patched on TR-48.
- (3) All reference voltages (± 10v) used on TR-10 were taken from the TR-48.
- (4) All voltages of OMRAC programming were checked with the same digital voltmeter on the TR-48.
- (5) The major parts of the OMR and OAC programming were patched on the same computer as each other.
- (6) Static checks of each group of all OMRAC patching circuits was made (Tables 7.2 to 7.7.)
- (7) Static check of each input from process equipment and output to process equipment (Figs. 8.6, 8.7 and 8.8). was made.
- (8) Dynamic check of OMR and OAC with constant parameter was made (usually these two responses will be approximately the same.

All static and dynamic checks shown in (6), (7) and (8) are important preparatory procedures before every on-line operation.

9.3. Smooth plot of fluctuating reactor temperature

 $\left[\begin{array}{c} \frac{T}{T_m} \end{array}\right]$ from the existing temperature transmitter is varying within $^{\pm}$ 0.1°C. Apparently it is impossible to plot a smooth phase-plane curve with the X-Y plotter for such a narrow operating range (See 9.1). Thus a <u>filter technique</u> was used (Fig.9.1.) and the smoother out reactor temperature is also shown in Fig.9.1.

By using this simple technique, all phase-plane trajectories of on-line computer OMRAC were plotted and are shown in Chapter 10.

9.4. Effect of initial temperature setting for partially simulated CSTR

From Chapter 7, Table 2, the initial comditions of on-line operation are:

$$C(t_0) = 0.135 \text{ mol/litre} \text{ or } \left[\frac{C(t_0)}{C_m}\right] = 0.135 \text{ mu}.$$

$$T(t_0) = 33^{\circ}C$$
 or $\left[\frac{T(t_0)}{T_m}\right] = 0.33 \text{ mu}$

 $C(t_0)$ was set on the computer and $T(t_0)$ on the process. While this appears straightforward from the test run, the $T(t_0)$ setting gave considerable trouble and is discussed in detail.

To illustrate the operational situation a simple calculation was made from experimental data of the test run:

(1) At initial conditions:
$$\left[\frac{K}{K_m}\right] = 0.45 \text{ mu}, \left[\frac{C(t_0)}{C_m}\right] = .135 \text{ mu}$$
 from equation (8-4):

$$\left[\begin{array}{c} \frac{Q_g}{Q_{gm}} \right] = 10.66 \left[\begin{array}{c} 1 \end{array}\right] \left[.45 \end{array}\right] \left[.135\right] = 0.648 \text{ mu} = 6.48 \text{ v.}$$

= $6.48 \text{ Kcal } \times 10^3/\text{h}$

from Fig. A. 4.17, then

$$\left[\frac{Q_g}{Q_{gm}} \right] \cong$$
 80 variac reading (VR)

(2) Corresponding to VR = 80

$$F_c = \frac{Q_g - F \Delta T}{T_c} = \frac{6480 - 3 \times 60 \times (33 - 17.5)}{15}$$

= 4.9 litre/min.

(3) From experimental data at final steady state

$$F_c = 1.54 \, \text{litre/min}$$

VR = 54.

The following possible methods for setting up initial temperature $(T(t_0) = 33^{\circ}C)$ are suggested:

Method,1: Set variac reading directly from computer (see Fig. 8.7); set F_c = 1.54 litre/min when reactor temperature is at T(t_o) = 33°C (or VR = 80); then start to operate the computer. Theoretically after operating, the reactor temperature should decrease immediately (Fig. 9.2). But in fact, the temperature will still increase first and then decrease as shown in Fig. 9.2. and the corresponding concentration response curves without and with optimal control (parameters constant) are also shown in Figs. 9.3 and 9.4 respectively.

Method 2: Manually set the variac reading at 60, until the initial steady state is obtained $T(t_0) = 33^{\circ}C$ and then start to operate the computer.

In fact the variac reading will be increased at the beginning from 60 to 80 and then decreased. Thus, more heat must be generated by the immersion heater, so that the reactor temperature also increases first and then decreases as shown in Figs. 92, 9.3 and 9.4.

Method 3: Set variac reading at 80 and $F_c = 4.9$ litre/min (the calculated initial steady state condition), until $T(t_o) = 33^{\circ}C$, and then start to operate the computer.

In fact, the variac reading now decreases but F_c immediately drops from 4.9 litre/min to $\stackrel{\frown}{=}$ 1.54 litre/min followed by a large heat release. Thus the reactor temperature also increases then decreases; this fact is the same in Method 2.

None of the above methods can make the reactor temperature decrease immediately after starting, and there is an apparent large offset from the theoretical response curves (Figs. 9.2, 9.3 and 9.4)

Eventually a switching shift technique was used and solved this difficulty. The operating procedure is shown below:

(1) Manually set the variac reading at an appropriate value (usually 60)

Switching method:

- (2) Computer operates F_c from $\left[\frac{F_{cs}}{F_{cm}}\right]$ directly (see Fig. 8.8).
- (3) Adjust $\left[\frac{F_{cs}}{F_{cm}}\right]$ initial to give the initial steady state, $T(t_0) = 33^{\circ}C$.

- (4) Set SW-1 in Fig. 8.7 to L position to make $e_f = 0$.
- (5) Start to operate the computer. The variac reading will immediately decrease.
- (6) Shift the switch SW-1 from L to R (normal condition) at a certain time determined by experiments.

The result is shown in Figs. 9.2 to . 9.4 and it is much better and very close to the theoretical response curves.

9.5. Determination of $\left[\frac{F_{cs}}{F_{cm}}\right]$ final

 $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ has been defined in 8.3.4. as actual cooling water flowrate at final steady state of on-line computer operation, converted to volts and set on Pot 08 in Fig.8.8. To set an accurate $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ value before operation an iteration method was used as follows:

lst iteration: Set
$$\left[\frac{F_{cs}}{F_{cm}}\right]_{final} = \left[\frac{F_{cs}}{F_{cm}}\right]_{initial}$$

operate and find Fc at final steady state

$$as\left[\frac{F_{cs}}{F_{cm}}\right]_{fl}$$

2nd iteration:
$$Set\left[\frac{F_{cs}}{F_{cm}}\right]_{fl} = \left[\frac{F_{cs}}{F_{cm}}\right]_{f}$$

operate and find F_c at final steady state

$$as \left[\frac{F_{cs}}{F_{cs}} \right]_{f2}$$

3rd iteration: Set
$$\left[\frac{F_{cs}}{F_{cm}}\right]_{f2} = \left[\frac{F_{cs}}{F_{cm}}\right]_{f1}$$

operate and find F at final steady state until:

$$\left[\begin{array}{c} \frac{F_{cs}}{F_{cm}} \right]_{fi} \longrightarrow \left[\begin{array}{c} \frac{F_{cs}}{F_{cm}} \end{array} \right]_{f(i-1)} .$$
then set
$$\left[\begin{array}{c} \frac{F_{cs}}{F_{cm}} \end{array} \right]_{fi} \quad \text{as} \left[\begin{array}{c} \frac{F_{cs}}{F_{cm}} \end{array} \right]_{final} \quad \text{on Pot 08.}$$

By using this iteration method to determine an accurate value of $\left\lceil \frac{F_{cs}}{F_{cm}} \right\rceil$ and the switching method for initial value setting, then more reliable (close to theoretical) and reproducible on-line computer operation was obtained and is shown in Figs. 9.5 and 9.6 and the corresponding curves in Figs. 9.3 and 9.4.

9.6. Effect of Feed flowrate step change on partially simulated CSTR

For on-line computer OMRAC operation when feed flowrate (F) decreases (or increases) by a step change, using switching and iteration methods discussed in 9.4 and 9.5, the process dynamic response (not optimal control, nor OMRAC) for on-line computer operation should be close to the theoretical process dynamic response with the same step change shown in Chapter 7. However, the results apparently gave certain differences (see Chapter 10, Figs 10.1 and 10.2) which need to be explained.

A <u>compensation technique</u> was introduced for comparison of the following two different operations:

1. Completely simulated operation:

When F decreases and is set on the computer before operation the computer is started, there is no effect on the whole system.

2. Partially simulated operation:

When F decreases and is set on the process, it produces an implicit effect. This effect does not influence the dynamic response but it can influence the initial steady state.

i.e. If F decreases, the reactor temperature at the initial steady state increases and vice versa.

The best way to compensate for such an effect is to decrease or increase the value of $\left[\begin{array}{c} F_{\text{cs}} \\ F_{\text{cm}} \end{array}\right]_{\text{initial}}$ according to whether F decreases or increases.

The accurately compensated $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ is obtained either by approximate simple energy balance calculation or by the iteration method shown in 9.5. The iteration method is preferred because the compensated $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ can be measured directly.

By using the compensated $\left[\frac{F_{cs}}{F_{cm}}\right]_{final}$ (set on Pot 08 in Fig. 8.8), the final dynamic response of on-line computer operation is in excellent agreement with the theoretical results shown in Chapter 10.

Two types of on-line computer operation for a partially simulated CSTR were defined as follows:

- Type 1: without compensation was called:

 Partial Simulated Process On-line Operation
 or Type 1 Operation.
- Type 2: with compensation was called:

 Approach to Real Process On-line Operation
 or Type 2 Operation.

 (see Chapter 10)

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CHAPTER 10

OPERATION AND ANALYSIS OF ON-LINE COMPUTER

OMRAC

10.1. On-line computer OMRAC operation

In Chapter 8, a rigid on-line computer OMRAC system design was presented and in Chapter 9, the solutions of all difficulties for on-line computer operation with a very narrow operating range are given. All kinds of operating cases and groups, all kinds of figure plotting for each case, and all types of different operations within each figure are almost the same as in Chapter 7 (7.6). Thus the results from the theoretical complete simulation (Chapter 7) and the practical on-line operation of OMRAC can be compared almost case by case, figure by figure and curve by curve.

All tests of on-line computer operation of OMRAC are shown in Table 10.1.

General operating conditions: (same as in 7.7.1)

- (1) Initial conditions (lst quadrant) $C(t_0) = 0.135 \frac{\text{mol}}{\text{litre}} ; T(t_0) = 33^{\circ}C$
- (2) Final desired reactor concentration $C(t_f) = 0.09 \frac{\text{mol}}{\text{litre}}$
- (3) OMR : $K_1 = K_2 = 8$
- (4) OAC : Optimal P $K_3 = 100, 200, 500$ and 1000.

TABLE 10.1.
On-line computer OMRAC operation

			*		2 22
Group	Case	Operation conditions	Type of operation	Kind of figure	Figure
1	1.1	F decrease 10%	1	A	10.1
		"	ı	В	10.2
		"	1	С	10.3
	1.2	F decrease 20%	1	A	10.4
		11	1	C	10.5
	1.3	F decrease 10%	2	A	10.6
		**	2	В	10.7
		"	2	C	10.8
	1.4	F decrease 20%	2	A	10.9
		11	2	С	10.10
2	2.1	F increase 10%	2	A	10.11
		11	2	В	10.12
		11	2	С	10.13
	2.2	F increase 20%	2	Λ	10.14
		"	2	C	10.15
٠	2.3	F increase 20%	1	A	10.16
		n .	1	C	10.17
3	3.1	a exponential decay 20	0% 2	A	10.18
		н	2	C	10.19
	3.2	a exponential decay 30	0% 2	A	10.20
		11	2	C	10.21
	3.3	a exponential decay 40	0% 2	A	10.22
		н	2	В	10.23
		11	2	С	10.24

Table 10.1 (continued)

Group	Case	Operation conditions	Type of operation	Kind of figure	Figure
3	3.4	a exponential decay 40% (for high weighting factors)	2	A	10.25
		11	2	С	10.26
4	4.1	Combined parameters	1	A	10.27
		(F decrease 10% change ((a decay 20%	1	С	10.28
	4.2	II .	2	A	10.29
		TT .	2	В	10.30
		n .	2	С	10.31
5		(Group 4) (Optimal P+I)			
	5.1	$K_3 = 100, \epsilon = 0, 1, 2, 3$	2	A	10.32
		11	2	С	10.33
	5.2	K ₃ = 100, 6 = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0	2	А	10.34
		11	2	В	10.35
		II .	2	C	10.36
	5.3.	$K_3 = 200,$ $E = 0.0, 0.2, 0.4, 0.6,$ $0.8, 1.0$	2	A	10.37
		II .	2	В	10.38
6	10	(Group 4) (Optimal P + I + D)			
	6.1.	$K_3 = 1, \xi = 0.1, 0.2, 0.3, 0.4.$	2	A	10.39
		, u	2	В	10.40

TABLE 10.1 (continued)

Group	Case	Operation conditions	Type of operation	Kind of Figure	Figure
6	6.2	(K = 1, & = 0.4 (40 min. operation	2	A	10.41 .
		· u	2	В	10.42
	6.3	$K_3 = 10, \ \epsilon = 0.0, 0.04, 0.08, 0.12$, 2	A	10.43
		11	2	В	10.44
		"	2	C	10.45
	6.4	(K ₃ = 10, £ = 0.12 (40 min. operation	2	A	10.46
		"	2	В	10.47
	6.5	$K_3 = 20, \ \epsilon = 0.0, 0.04, 0.08, 0.12$	2	A	10.48
		<u>.</u> 11 -	2	В	10.49
7	*	(Group 4 (different initial (conditions))		
	7.1	$(C(t_0) = 0.15 \text{ mol/litre})$) 2	A	10.50
		$(T(t_0) = 28^{\circ}C$) 2	В	10.51
		((2nd quadrant)) 2	С	10.52
	7.2	$(C(t_0) = 0.07 \text{ mol/litre})$) 2	A	10.53
		$(T(t_0) = 27^{\circ}C$) 2	В	10.54
		((3rd quadrant)) 2	С	10.55
	7.3	$(C(t_0) = 0.06 \text{ mol/litre})$) 2	A	10.56
		$(T(t_o) = 34^{\circ}C$) 2	В	10.57
		((4th quadrant)) 2	С	10.58

TABLE 10.1 (continued)

Group	Case	Operation conditions		Type of operation	Kind of Figure	Figure
8		(Group 4 (different OMR				
•	8.1	(OAC : Optimal P (K ₃ = 200 .)	2	A	10.59
		$((I) K_1 = K_2 = 4)$ $((II) K_1 = K_2 = 15)$)	2	В	10.60
9 .		(Group 4 (different set point				
	9.1	(OAC : Optimal P)	2	Λ	10.61
3 .0		(K ₃ = 200 ((I) C _d : 0.10 mol/ (litre ((II) C _d : 0.08 mol/ litre	,	2	В	10.62
10	*	(Group 4 (different inlet (concentration		*		
	10.1	(C as load variable)	2	A	10.63
5		(C as load variable (C : 0.9 mol/litre)	2	В	10.64
	10.2	(C as load variable)	2	A	10.65
		(Co : 1.1 mol/litre)	2	В	10.66
٠	10.3	(C as parameter)	2	Α .	10.67
		((I) C ₀ = 0.9 mol/ (litre ((II) C ₀ = 1.1 mol/ (litre))))	2	' В	10.68

10.2. Comparison of Type 1 and Type 2 on-line operation

From definition (9.6) Type 1 operation is only for the partially simulated process without compensation. Actually this type of dynamic response does not exist on the real process and Type 2 operation called approach to real process operation applies to the partially simulated process but with compensation. From all experiments on on-line operation, the dynamic response and phase-plane trajectories of Type 2 operation are different from Type 1 operation, but in good agreement with the theoretical results of complete simulation.

Since a very narrow operating range has been planned and used, the highly sensitive performance of different on-line operations such as: UC, UOC, OMRAC, and OMR of a CSTR can be plotted respectively for comparison with the theoretical results. (Figs. 7.7 to 7.54 and Figs. 10.1 to 10.68).

Thus partial simulation techniques have been extended to a highly sensitive and accurate performance operation from Buxton's original design by using compensation combined with switching and iteration methods.

10.3. Comparison and analysis of process dynamics response and phaseplane trajectories

10.3.1. For any individual and combined unmeasurable parameters with different possible conditions (from Group 1 to Group 10), all dynamic response curves and phase-plane trajectories of on-line operation are in good agreement with the theoretical results and also follow a definite smooth, regular and

effective order as shown below:

(US)
$$\rightarrow$$
 (UOC) \rightarrow (K₃=100 \rightarrow 200 \rightarrow 500 \rightarrow 1000) \longrightarrow (OMR) where \rightarrow indicates more offset from OMR

- 10.3.2. From the dynamic response curves of on-line operation with the same test conditions as in the theoretical results, the response of OMRAC is always better than UOC and approaches OMR as a limit as the weighting factor is increased.
- 10.3.3. From the dynamic response curves of on-line operation with the same test conditions as in the theoretical results, the adaptation of OMRAC has no limitations for any operating conditions. The only limitation is the constraints of the optimal control law which corresponds to the control valve minimum and maximum capacity for cooling water flowrate.
- 10.3.4. From all phase-plane trajectories of on-line operation, the final steady state point of OMRAC is changed, and approaches the desired reactor concentration of OMR as a limit when the weighting factor K₃ is increased; it never returns to the original steady state point of OMR, because of the change of parameters. This phenomenon was illustrated earlier in Chapter 3. (3.3 and Fig.3.3.)
- 10.3.5. In general all process responses of on-line operation are comparatively more sensitive than the theoretical responses from complete simulation.

10.4. Comparison and analysis of optimal control law

10.4.1. All optimal control laws for the complete simulation and on-line operation are plotted by the X-Y plotter with different units: Kcal/min for complete simulation; U* and m* and litre/min for on-line operation, F_c.

The relation between then has been discussed in (8.3.4.) from equation (8-9):

$$\begin{bmatrix} \frac{F_{c}}{F_{cm}} \end{bmatrix} = \begin{bmatrix} \frac{F_{cs}}{F_{cm}} \end{bmatrix} + \frac{0.1 \left[\frac{U^{*}}{Q_{cm}} \right]}{\left[\frac{\Delta T_{c}}{T_{m}} \right]}$$
or $F_{c} = (F_{cs})_{final} + \left(\frac{0.1 F_{cm} \times T_{m}}{Q_{cm}} \right) \left(\frac{U^{*}}{\Delta T_{c}} \right)$

Simplifying gives:

$$F_{c} = (F_{cs})_{final} + \frac{U^{*}}{\Delta T_{c}}$$
 (10-1)

and
$$F_c = (F_{cs})_{final} + \frac{m^*}{\Delta T_c}$$
 (10-2)

where (F_{cs}) final = cooling water flowrate at the final steady state.

In fact both $(F_{cs})_{final}$ and F_{cs} are slightly different in each experiment, but such changes are comparatively small and shown in Appendix 6 (Tables A.6.1 to A.6.10). So the dynamic response curves both for U* (or m*) and F_{cs} can be compared and evaluated correspondingly.

10.4.2. All of the optimal control laws both for theoretical and on-line operation may be arranged in the following order of effectiveness:

$$\begin{pmatrix} K_3 = 1000 \rightarrow 500 \rightarrow 200 \rightarrow 100 \\ \text{and } F_c & \text{and } F_c & \text{and } F_c \end{pmatrix}$$

- 10.4.3. In general the response of F_c for on-line operation is more sensitive than U* (or m*) in theoretical complete simulation. This effect will influence the process response discussed in 10.3.5.
- 10.4.4. The response of the optimal P + I + D control law always fluctuates since a large value of \$\beta\$_{27} is produced (Appendix A.2.7 and Fig. 10.45).

10.5. Comparison and analysis of optimal PID control

10.5.1. Optimal P+I and Optimal P + I + D of OMRAC for on-line operation can produce the same improved performance as Optimal P alone in complete simulation.

Optimal integral control (optimal P + I or P + I + D)

in on-line operation is more sensitive than the corresponding
theoretical cases and the optimal integral control weighting
factor & is much smaller when used for on-line operation, and
is discussed below:

10.5.2. For Optimal P + I

In complete simulation: The performance in cases 5.1 and 5.2 (Figs. 7.29 to 7.33) is always excellent as & increases.

Case 5.1.	Case 5.2
K ₃ = 100	K ₃ = 200
= 0, 1, 2, 3, 4	= 0, 1, 2, 3, 4,
	8 and 15
$\left(\frac{K_3}{\mathfrak{t}}\right)_{\min} = \frac{100}{4} = 25$	$\left(\frac{\kappa_3}{\epsilon}\right)_{\min} = \frac{200}{15} = 13.3$

where $\binom{K_3}{f}$ min is the minimum weighting factor ratio between K_3 and used for Optimal integral control adjustment.

In on-line operation: The performance in cases 5.2 and 5.3 (Figs. 7.34 to 7.38) is much better than in case 5.1 (Figs. 7.32 and 7.33).

Case 5.1.	Case 5.2	Case 5.3
K ₃ = 100	K ₃ = 100	K ₃ = 200
= 0, 1, 2, 3.	= 0, .2, .4, .8,	= 0, .2, .4, .8,
$\left(\frac{K_3}{\epsilon}\right)_{\min} = 33.3$	$\left(\frac{K_3}{\epsilon}\right)_{\min} = 100$	$\left(\frac{K_3}{\epsilon}\right)_{\min} = 200$

From the above analysis of Optimal P + I, for complete simulation the performance of the OMRAC is always excellent even if $\left(\frac{K_3}{\epsilon}\right)_{\min}$ decreases to 13.3. But for on-line operation, the best value of $\left(\frac{K_3}{\epsilon}\right)$ is kept around 100 or $\left(\frac{K_3}{\epsilon}\right)$ \longrightarrow 100

10.5.3. For Optimal P + I + D

In complete simulation: The performance in cases 6.1 and 6.2 (Figs. 7.34 to 7.37) is always excellent as increases

Case 6.1.	Case 6.2.		
K ₃ = 1.0	K ₃ = 3.0		
= 0.5, 1, 1.5, 2.0	= 0, .5, 1.5, 2.0		
$\left(\frac{K_3}{\epsilon}\right)_{\min} = 0.5$	$\left(\frac{K_3}{\epsilon}\right)_{\min} = 1.5$		

In on-line operation: The performance in cases 6.3. and 6.3 (Figs. 10.43 to 10.49) is much better than case 6.1 (Figs. 1039 and 10.40).

Case 6.1.	Case 6.3.	Case 6.5.
K ₃ = 1.0	K ₃ = 10.0	K ₃ = 10.0
= .1, .2, .3, .4	= 0,.04,.08,	= 0, .04, .08,
$\left(\frac{K_3}{\epsilon}\right)_{\min} = 2.5$	$\left(\frac{K_3}{\epsilon}\right)_{\min} = 83.8$	$\left(\frac{K_3}{\epsilon}\right)_{\min} = 186.6$

Note. When f = 0, it reduces to Optimal P + D control.

From the above analysis of Optimal P + I + D for complete simulation the performance of OMRAC is always excellent even if $\left(\frac{K_3}{\epsilon}\right)_{\text{min}}$ decreases to 1.5. But for on-line operation, the best value of $\left(\frac{K_3}{\epsilon}\right)$ is kept around

$$\left(\frac{K_3}{\epsilon}\right)$$
 \longrightarrow 80

In general for Optimal PID control of on-line operation the best value of $\binom{K_3}{\ell}$ will be:

$$\left(\frac{K_3}{\xi}\right) - 80 - 100 \tag{10-3}$$

10.6. Comparison and analysis of OMRAC stability

10.6.1. In the process control field all techniques used for system stability analysis such as Routh-Hurwitz, Nyquist and Liapunov stability criterion give the theoretical prediction for stability analysis from the derived system equations, and by using such techniques the system stability cannot make predictions for on-line operation. The most straightforward method to determine the system stability of on-line OMRAC is by direct use of the many dynamic response curves and phase-plane trajectories obtained from the X - Y plotter.

From the general definition of process stability (73), the comparison and analysis of OMRAC stability is shown below.

10.6.2. In general the system stability both for theoretical complete simulation and on-line operation possesses the following order of effectiveness:

OMRAC

(OMR)
$$\leftarrow$$
 $\left(K_3 = 1000 \leftarrow 500 \leftarrow 200 \leftarrow 100\right) \leftarrow$ (UOC) \leftarrow (US)

where \leftarrow indicates increasing stability.

10.6.3. Since the response of optimal control law in on-line operation of the process is always more sensitive than the theoretical case (10.3.3. and 10.4.3.) then in general the theoretical system response of OMRAC is always more stable

than on-line operation but the latter can still possess excellent asymptotic stability in different operating conditions.

10.6.4. From Group 7 since different initial conditions are selected from the four different quadrants around the original final steady state (or $C(t_f) = 0.09$ mol/litre; $T(t_f) = 30^{\circ}C$), all response curves of OMRAC (Figs.10.50 to 10.58) still possess excellent asymptotic stability; thus, by definition, on-line OMRAC is asymptotically stable in the large.

10.6.5. Stability in Optimal PID control

From Section 5 analysis (10.5.2. and 10.5.3) the Optimal PID operation of OMRAC will maintain excellent stability when the weighting factor ratio is set as in equation 10-3, or:

$$\frac{K_3}{\epsilon}$$
 \longrightarrow 80 - 100

There are several interesting figures of Optimal P+I+D obtained over a long time of operation (20 min. for dynamic response. Figs. 10.41, 10.46 and 40 min. for phase-plane, Figs. 10.42 and 10.47). For comparison of the stability of each pair of figures (10.41 and 10.46, 10.42 and 10.47), the latter one $\frac{K_3}{\epsilon} = 83.3$ is much more stable than the first $\frac{K_3}{\epsilon} = 2.5$.

10.7. Q and (-AH) calculations from experimental data

All experimental data of the final steady state conditions for on-line operation are shown in the Appendix, Tables 6.1 to 6.10.

From the many on-line experimental tests, Q_g and (- Δ H) were

calculated and checked as follows:

 $\mathbf{Q}_{\mathbf{g}}$: $\mathbf{Q}_{\mathbf{g}}$ values can be checked for each operating case by using the following different calculations:

(1) Q_{σ} calculated from equation (8-4)

$$Q_{g} = 10.66 \ Q_{gm} \left[\frac{a}{a_{m}} \right] \left[\frac{K}{K_{m}} \right] \left[\frac{C}{C_{m}} \right] \left(\frac{Kcal \times 10^{3}}{h} \right)$$

or

$$Q_g = 29613.48 \left[\frac{a}{a_m} \right] \left[\frac{K}{K_m} \right] \left[\frac{C}{C_m} \right] \left(\frac{\text{cal}}{\text{sec}} \right)$$
 (10-4)

where $\left[\begin{array}{c} \frac{a}{a_m} \end{array}\right] \left[\begin{array}{c} \frac{K}{K_m} \end{array}\right] \left[\begin{array}{c} \frac{C}{C_m} \end{array}\right]$ is in machine units or mu.

- (2) Q calculated directly from variac reading by using the calibration curve (Fig. A.4.16)
- (3) Q_g calculated from equation (7-7)

$$Q_{g} = \rho_{c}C_{pc}F_{c}\Delta T_{c} + \rho_{c}C_{p}F(T - T_{i})$$

or
$$Q_g = 16.7 \left(F_c \Delta T + F \left(T - T_i\right)\right) \left(\frac{cal}{sec}\right)$$
 (10-5)

(- Δ H): (- Δ H) value was checked from the previously calculated theoretical value (18511 $\frac{\text{cal}}{\text{g.mole}}$) (7.4 and Fig. 7.8) as follows

From equation (7-8)

$$(-\Delta H) = \frac{(Q_g)_{AV}}{aVKC_g} = \frac{(Q_g)_{AV}}{16a_m \cdot K_m \cdot C_m \left[\frac{a}{a_m}\right] \left[\frac{K}{K_m}\right] \left[\frac{C}{C_m}\right]}$$

OR
$$(-\Delta H) = \frac{(Q_g)_{AV}}{1.6 \left[\frac{a}{a_m}\right] \left[\frac{K}{K_m}\right] \left[\frac{C}{C_m}\right]}$$
 (10-6)

where
$$(Q_g)_{AV} = (Q_g)_1 + (Q_g)_2 + (Q_g)_3$$
 / 3

All calculated Q_g and $(-\Delta H)$ values are shown in Tables 10.2 to 10.11 and the following ten tables show that:

- (1) Q values calculated from three different kinds of method for all different on-line operations, are in excellent agreement for each operating case.
- (2) (- ΔH) values in all different cases for on-line operation are in excellent agreement with the originally calculated theoretical value of:

$$(-\Delta H) = 18511 \frac{\text{cal}}{\text{mol}}$$

 Q_g and (- Δ H) values calculated from on-line experimental data for cases 1.1 and 1.2 (Theoretical value of (- Δ H) = 18511 $\frac{cal}{mol}$)

TABLE 10.2

	Q cal/sec			(- AH) cal mol	
	(1)	(2)	(3)	(Qg)AV	mol mol
Case 1.1					
บร	823	822	834	826.33	18570
UOC	800	806	816	807.35	18680
OMRAC					
K ₃ = 100	823	823	822	822.33	18488
K ₃ = 200	823	822	825	823.33	18510
K ₃ = 500	823	822	827	824.0	18525
K ₃ = 1000	823	822	832	825.6	18562
Case 1.2					
US	823	833	814	823.33	18510
noc	823	833	813	823.0	18503
OMRAC					
K ₃ = 100	823	828	823	824.67	18540
K ₃ = 200	823	828	817	822.67	18495
K ₃ = 500	823	822	824	823.0	18503
K ₃ = 1000	823	822	824	823.0	18503

TABLE 10.3.

 Q_g and (- Δ H) values calculated from on-line experimental data for cases 1.3 and 1.4 (Theoretical value of (- Δ H) = 18511 $\frac{cal}{mol}$)

·	Q _g cal/sec			(- AH) cal mol	
	(1)	(2)	(3)	(Qg)AV	(- Zh) mol
Case 1.3					
บร	800	806	808	804.67	18626
noc	817	822	824	821.0	18591
OMRAC					
K ₃ = 100	823	828	827	826.0	18570
K ₃ = 200	823	822	829	824.67	18540
K ₃ = 500	829	828	831	829.33	18512
K ₃ = 1000	829	828	833.	830.0	18527
K ₃ = 4000	829	828	834	830.33	18534
Case 1.4					
ນຣ	710	722	693	708.33	18446
пос	794	791	795	793.33	18501
OMRAC				İ	
K ₃ = 100	806	805	812	808.0	18566
K ₃ = 200	823	833	806	820.67	18450
K ₃ = 500	823	833	811	822.33	18487
K ₃ = 1000	829	840	812	827.0	18460

TABLE 10.4

Q and (- Δ H) values calculated from on-line experimental data for Cases 2.1, 2.2 and 2.3. (Theoretical value of (- Δ H) = 18511 $\frac{\text{cal}}{\text{mol}}$)

		Q _g			
	(1)	(2)	(3)	(Qg.)AV	(- AH) cal mol
Case 2.1.	(±)		*	3 4 325 : 235 :	
US	918	917	928	921.0	18569
noc	918	917	911	915.33	18454
OMRAC					·•
K ₃ = 100	918	917	925	920.0	18548
K ₃ = 200	918	917	935	923.0	18609
K ₃ = 500	918	917	927	920.67	18562
K ₃ = 1000	918.	917	922	919.0	18528
Case 2.2.	(S)				
US	977	970	995	980.67	18573
noc	977	970	1007	984.67	18648
OMRAC	9				
K ₃ = 100	977	970	998	981.67	18592
K ₃ = 200	977	970	992	979.67	18554
K ₃ = 500	977	970	990	979.0	18542
K ₃ = 1000	977	970	996	981.0	18580
Case 2.3		* .			
US	977	970	996	981.0	18580
uoc	977	970	993	980.0	18560
OMRAC					
K ₃ = 100	977	970	1005	984.0	18636
K ₃ = 200	977	970	998	981.67	18592
K ₃ = 500	977	970	1004	983.67	18630
K ₃ = 1000	977	970	997	981.33	18586

TABLE 10.5

 Q_g and (- Δ H) values calculated from on-line experimental data for cases 3.1, 3.2 and 3.3. (Theoretical value of (- Δ H) = 18511 $\frac{cal}{mol}$)

	T	କୃ (cal/sec		,, cal
	(1)	(2)	(3)	(Qg)AV	(- ΔH) cal mol
Case 3.1					
us	823	833	828	828.0	18615
noc	823	833	827	827.67	18608
OMRAC .					
K ₃ = 100	823	828	830	827.0	18593
K ₃ = 200	823	833	813	823.0	18503
K ₃ = 500	823	833	818	824.67	18540
K ₃ = 1000	823	833	817	824.33	18533
Case 3.2.					
US	800	791	812	801.0	18542
UOC	817	822	823	820.67	18584
OMRAC					1
K ₃ = 100	823	828	828	826.33	18578
K ₃ = 200	823	833	823	824.67	18540
K ₃ = 500	823	833	814	823.33	18510
K ₃ = 1000	823	833	817	824.33	18533
Case 3.3					
US	817	822	814	817.67	18516
UOC	817	822	814	817.67	18516
OMRAC			34.		
K ₃ = 100	823	830	822	825.0	18548
K ₃ = 200	823	830	819	824.0	18525
K ₃ = 500	823	830	828	827.0	18593
K ₃ = 1000	829	838	831	832.67	18586

 Q_g and $(-\Delta H)$ values calculated from on-line experimental data for cases 4.1 and 4.2. (Theoretical value of $(-\Delta H) = 18511 \frac{\text{cal}}{\text{mol}}$)

TABLE 10.6

		Q _g ca	l/sec		, cal
	(1)	(2)	(3)	(Q _g) _{AV}	(- ΔH) cal mol
Case 4.1					
us	918	917	928	921.0	18569
UOC	918	917	928	921.0	18569
OMRAC					
K ₃ = 100	918	923	919	920.0	18548
K ₃ = 200	918	923	918	919.67	18541
K ₃ = 500	930	931	930	930.33	18518
K ₃ = 1000	930	931	936.	932.33	18557
K ₃ = 4000	930	931	941	934.0	18590
Case 4.2.				•	
us ·	912	917	904	911.0	18486
noc	912	917	904	911.0	18486
OMRAC -					
K ₃ = 100	918	917	913	916.0	18468
K ₃ = 200	918	923	909	916.67	18481
K ₃ = 500	918	923	900	913.67	18421
K ₃ = 1000	918	926	907	917.0	18487
K ₃ = 4000	918	931	906	918.33	18515

TABLE 10.7

 Q_g and $(-\Delta H)$ values calculated from on-line experimental data for cases 5.1, 5.2 and 5.3. (Theoretical value of $(-\Delta H) = 18511 \frac{\text{cal}}{\text{mol}}$)

	1	Q _g	= cal/se	c	
	(1)	(2)	(3)	(Qg)AV	(-ΔH) cal mol
Case 5.1					
OMRAC					
K ₃ = 100					
E = 0 .	918	917	926	920.33	18555
£ = 1	918	917	937	924.0	18629
6 = .2	918	917	941	925.33	18656
· 6 = 3	918	917	944	926.33	18676
Case 5.2	¥		The second secon		
K ₃ = 100					
£ = 0	918	931	910	919.67	18542
£ = 0.2	918	931	913	920.67	18560
£ = 0.4	918	931	910	919.67	18542
£ = 0.6	918	931	920	923.0	18609
£ = 0.8	918	931	909	919.33	18535
£ = 1.0	918	931	909	919.33	18535
Case 5.3	,	**************************************			
OMRAC					
K ₃ = 200					
£ = 0	918	917	920	918.33	18515
£ = 0.2	918	917	935	923.33	18616
£ = 0.4	918	917	917	917.33	18495
£ = 0.6	918	917	943	926.0	18670
£ = 0.8	918	917	929	921.33	18575
£ = 1.0	918	917	938	924.33	18636

TABLE.10.8 $Q_{g} \ \mbox{and (- }\Delta\mbox{H) values calculated from on-line experimental data for Cases 6.1, 6.3 and 6.5}$

experimental	data	for	Cases	6.1,	6.3	and	6.
(Theoretical	value	of	(- AH) = 1	8511	mol)

		Q _g c	al/sec		cal
	(1)	(2)	(3)	(Qg)AV	(- AH) cal
Case 6.1					
noc	918	931	910	919.67	18541
OMRAC					
K ₃ = 1.0					
£ = 0.1	918	931	916	921.67	18582
£ = 0.2	918	931	930	926.33	18676
£ = 0.3	918	931	917	922.0	18589
£ = 0.4	918	931	922	923.67	18622
Case 6.3	918	923	911	918.0	18508
OMRAC					
K ₃ = 10					
£ = 0	918	928	920	922.0	18589
£ = 0.04	918	928	919	921.67	18582
£ = 0.08	918	928	928	924.67	18642
t = 0.12	918	928	927	924.33	18635
Case 6.5	(40)				
UOC .	918	923	913	918.0	18508
OMRAC					
K ₃ = 20					
f = 0	918	928	915	923.0	18607
£ = 0.04	918	928	915	920.33	18555
£ = 0.08	918	928	919	921.67	18582
E = 0.12	918	928	918	921.33	18575

TABLE 10.9

Q and (- Δ H) values calculated from on-line experimental data for Cases 7.1, 7.2 and 7.3 (Theoretical value of (- Δ H) = 18511 $\frac{\text{cal}}{\text{mol}}$)

		Q _g ca	l/sec		(- AH) cal		
	(1)	(2)	(3)	(Qg)AV	(- AH) mol		
Case 7.1							
us	918	917	924	919.67	18541		
noc	918	928	925	920.0	18548		
OMRAC							
K ₃ = 100	918	928	913	919.67	18542		
K ₃ = 200	918	928	915	920.33	18555		
K ₃ = 500	918	928	923	923.0	18609		
K ₃ = 1000	918	928	900	915.33	18454		
Case 7.2							
us	817	822	812	819.0	18546		
пос	829	833	832	831.33	18556		
OMRAC							
K ₃ = 100	859	850	868	859.0	18513		
K ₃ = 200	859	850	881	863.33	18606		
K ₃ = 500	859	850	888	865.67	18656		
K ₃ = 1000	859	850	865	858.0	18491		
Case 7.3			***************************************				
บร	888	889	890	889.0	18521		
UOC	918	917	905	913.33	18414		
OMRAC							
K ₃ = 100	918	917	942	925.67	18662		
K ₃ = 200	918	917	935	923.33	18615		
K ₃ = 500	918	917	933	922.67	18602		
K ₃ = 1000	918	917	922	919.0	18528		

 Q_g and $(-\Delta H)$ values calculated from on-line experimental data for Cases 8.1 and 9.1

(Theoretical value of $(-\Delta H) = 18511 \frac{cal}{mol}$)

TABLE 10.10

		Q _g ca	l/sec		(- AH) cal
	(1)	(2)	(3)	(Qg)AV	mor
Case 8.1					
K ₁ = K ₂ = 4	888	889	874	883.67	18410
OMRAC K ₃ = 200	918	917	913	916.0	18468
$K_1 = K_2 = 15$	ł	917	908	914.33	18434
OMRAC K ₃ = 200	918	917	906	913.67	18421
Case 9.1 (I) C _d = 0.10 mol /litre UOC	888	917	855	886.67	18472
OMRAC K ₃ = 200 (II)	918	917	909	914.67	18440
C _d = 0.08 mol /litre	000				.0
UOC OMRAC K ₃ = 200	918	917	861 915	916.67	18514 18481

TABLE 10.11 $Q_{g} \text{ and } (-\Delta H) \text{ values calculated from on-line}$ experimental data for Cases 10.1, 10.2 and 10.3 $(\text{Theoretical value of } (-\Delta H) = 18511 \frac{\text{cal}}{\text{mol}})$

		Q _p	cal/sec		221
	(1)	(2)	(3)	(Qg)AV	(- ΔH) cal mol
Case 10.1					
us	829	830	839	832.67	18586
uoc	859	861	854	858.0	18491
OMRAC K ₃ = 200	859	861	862	860.67	18549
Case 10.2					
US	977	985	983	981.66	18592
UOC	1007	1000	1005	1004.0	18456
OMRAC K = 200 3	1007	1000	1011	1006.0	18493
Case 10.3 (I) C = 0.9 mol/					
uoc	829	827	845	833.67	18608
OMRAC K ₃ = 200	829	827	853	836.33	18668
(II) C _o = 1.1 mol / litre					
noc	1007	1000	996	1001.0	18401
OMRAC K ₃ = 200	1007	1000	1016	1007.67	18523

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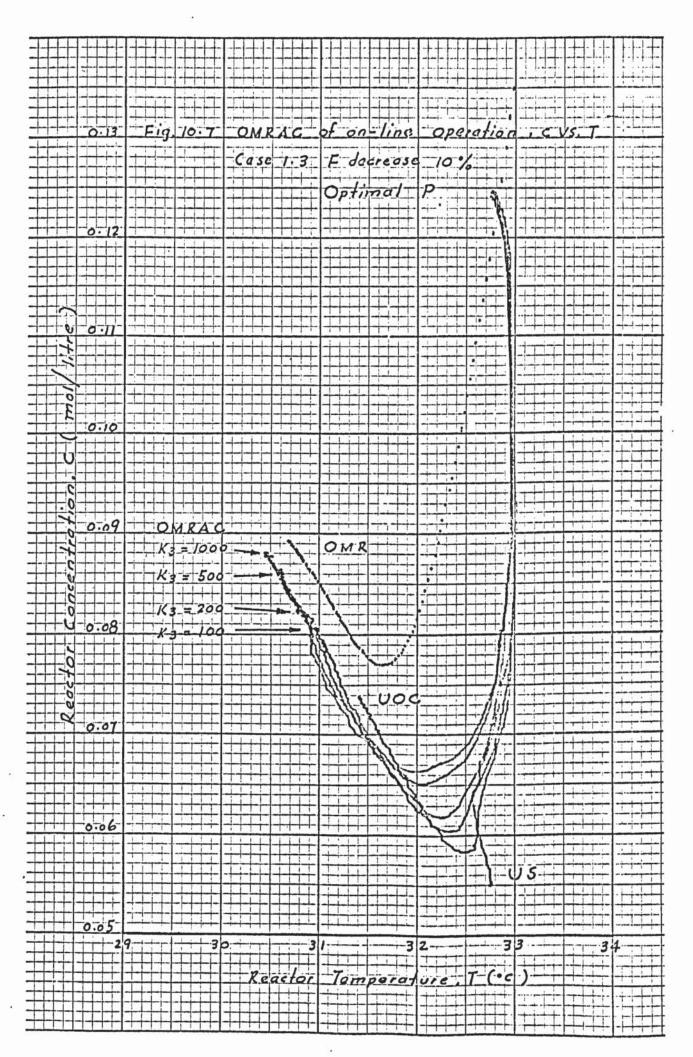
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Ro.o Rear Co.	K3 = 100 K3 = 500 K3 = 200 K9 = 100 U00								
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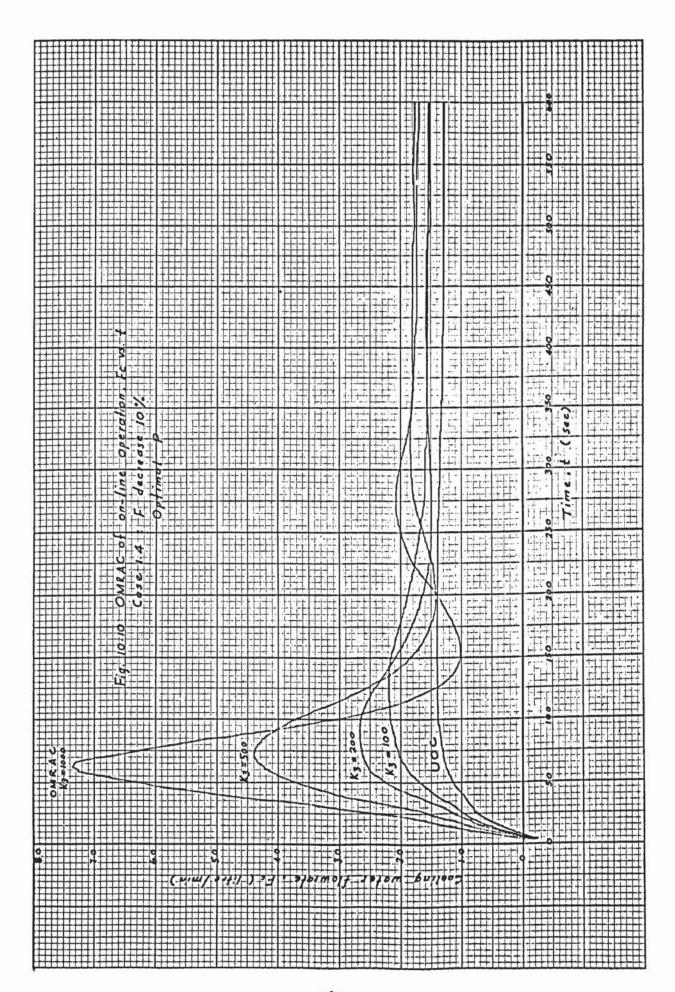
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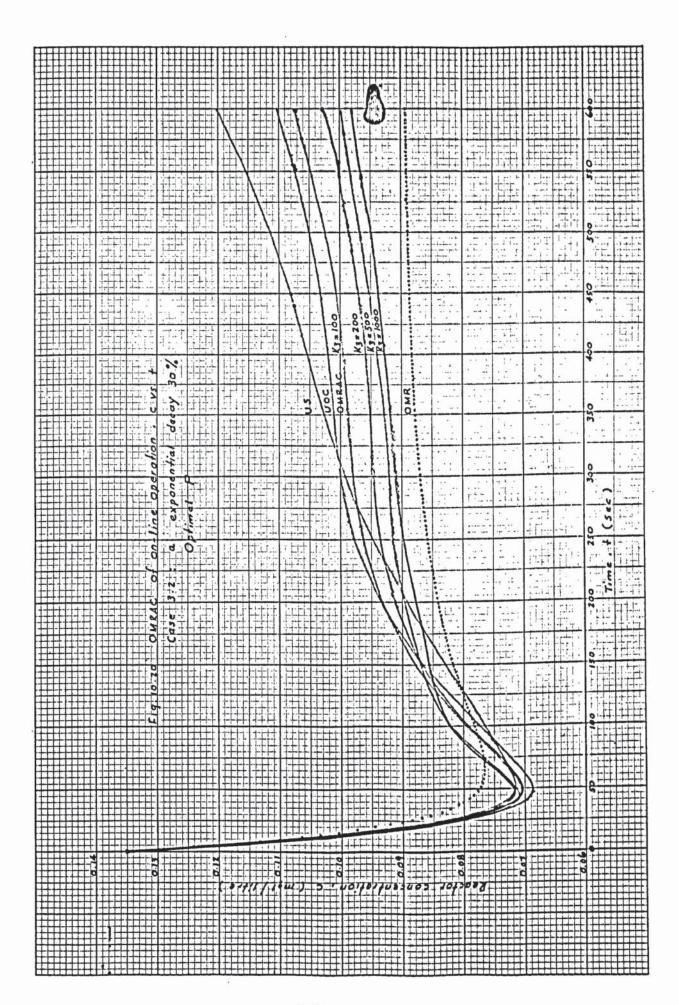
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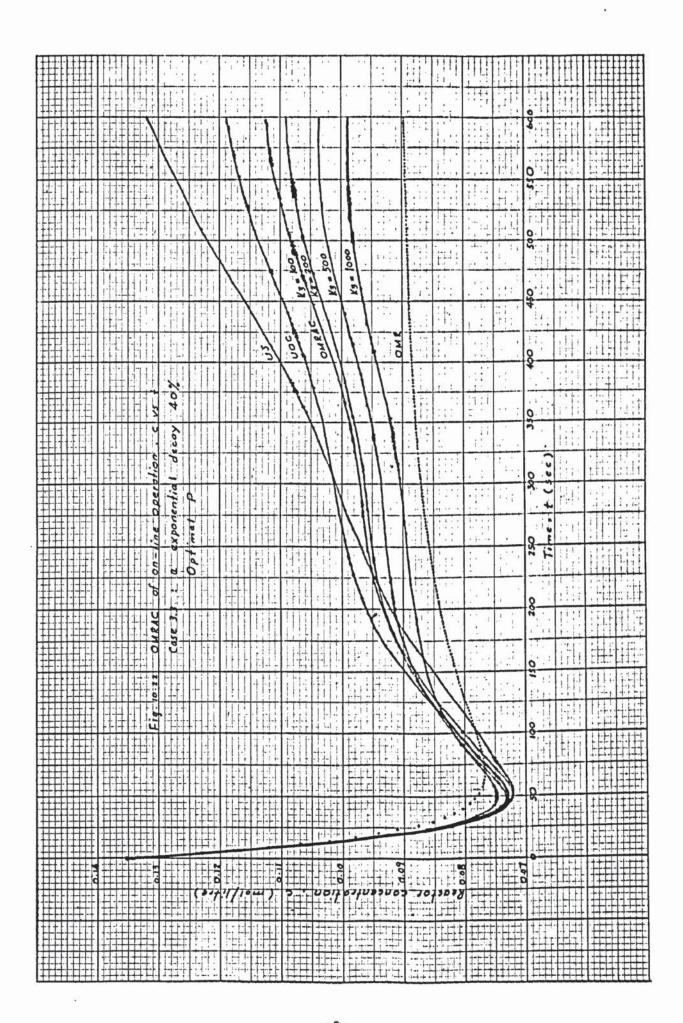
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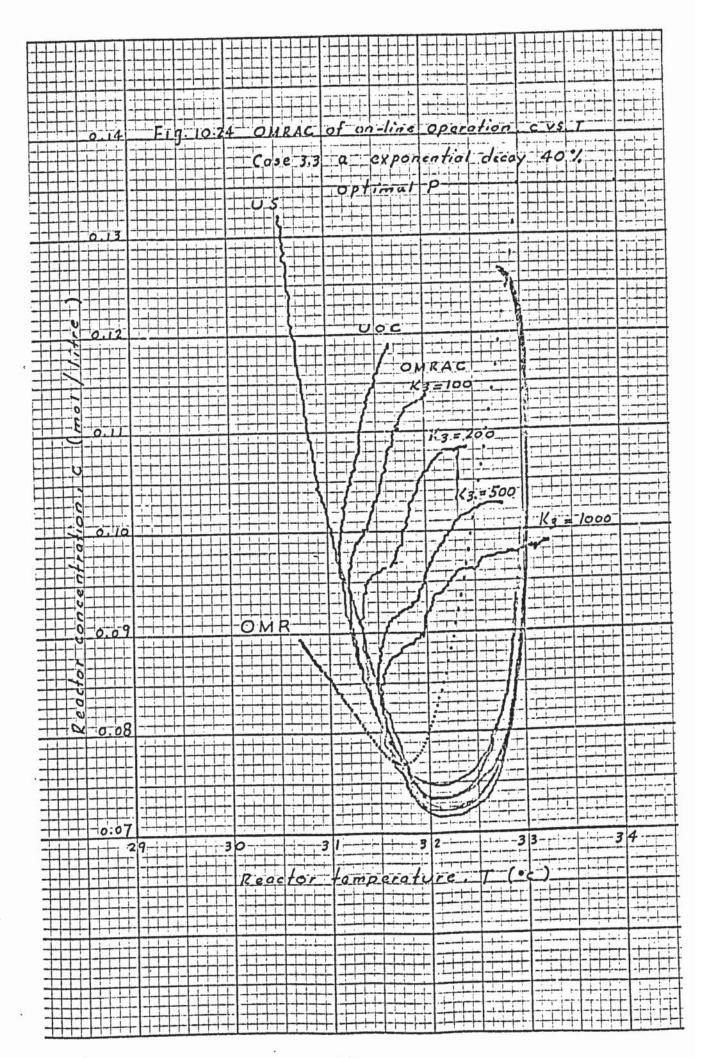
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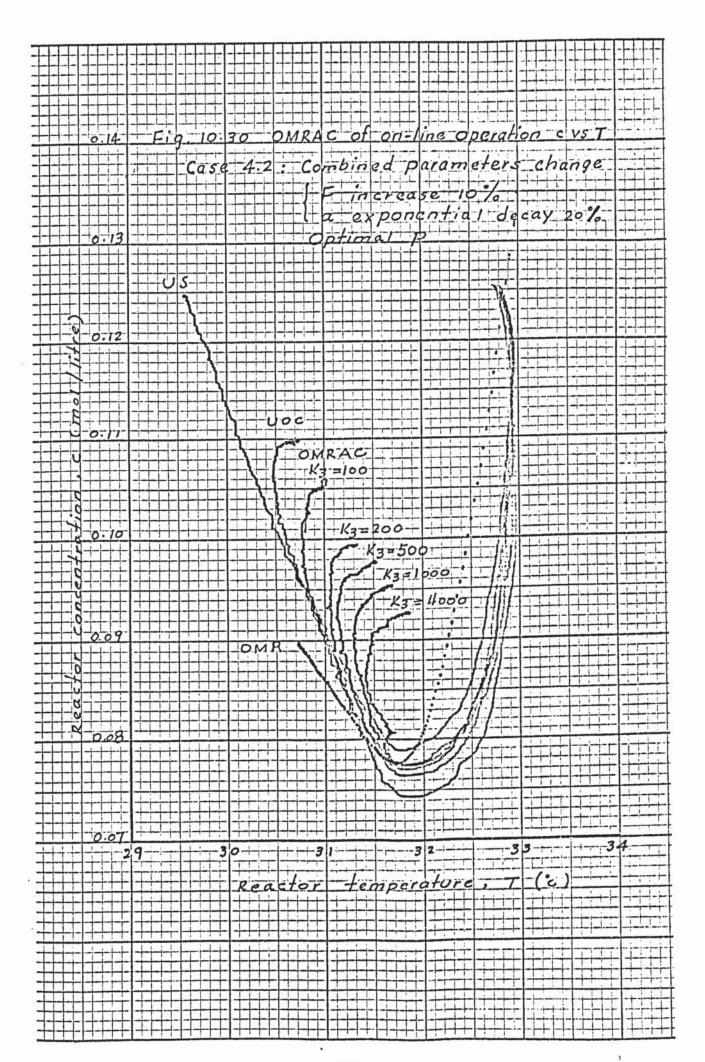
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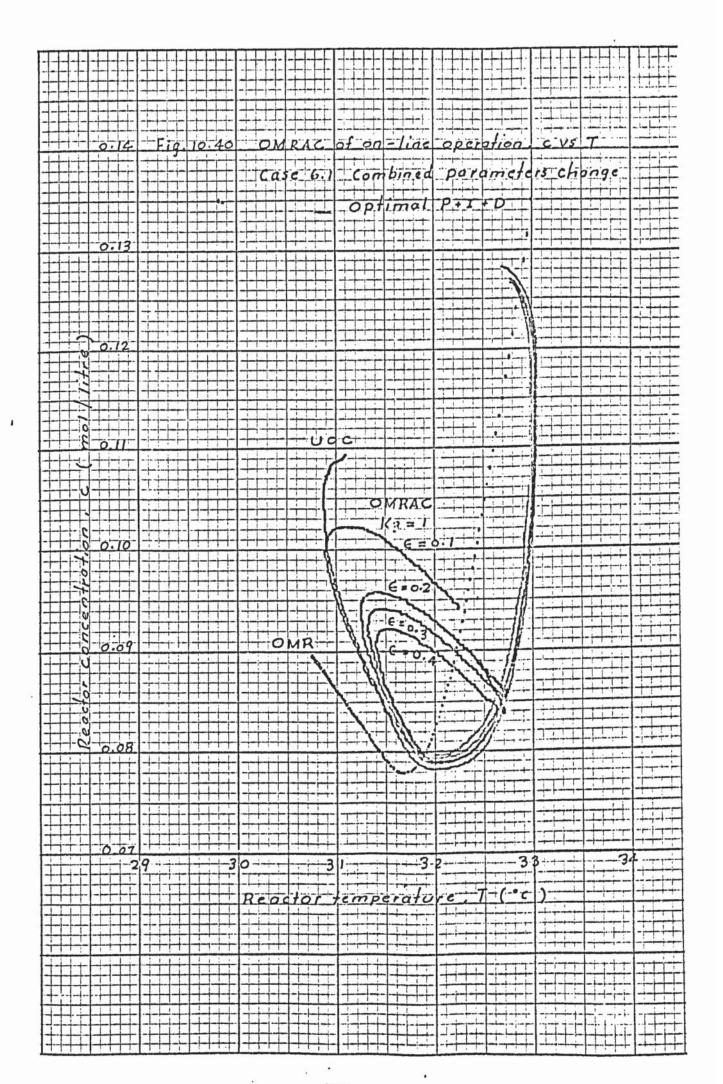
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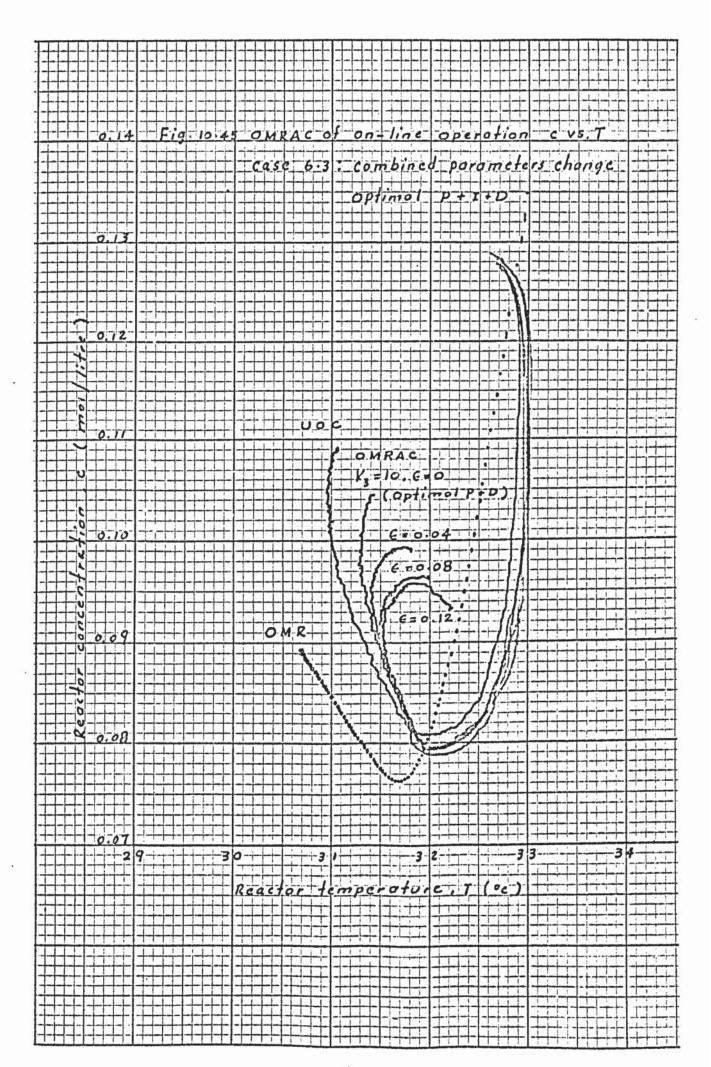


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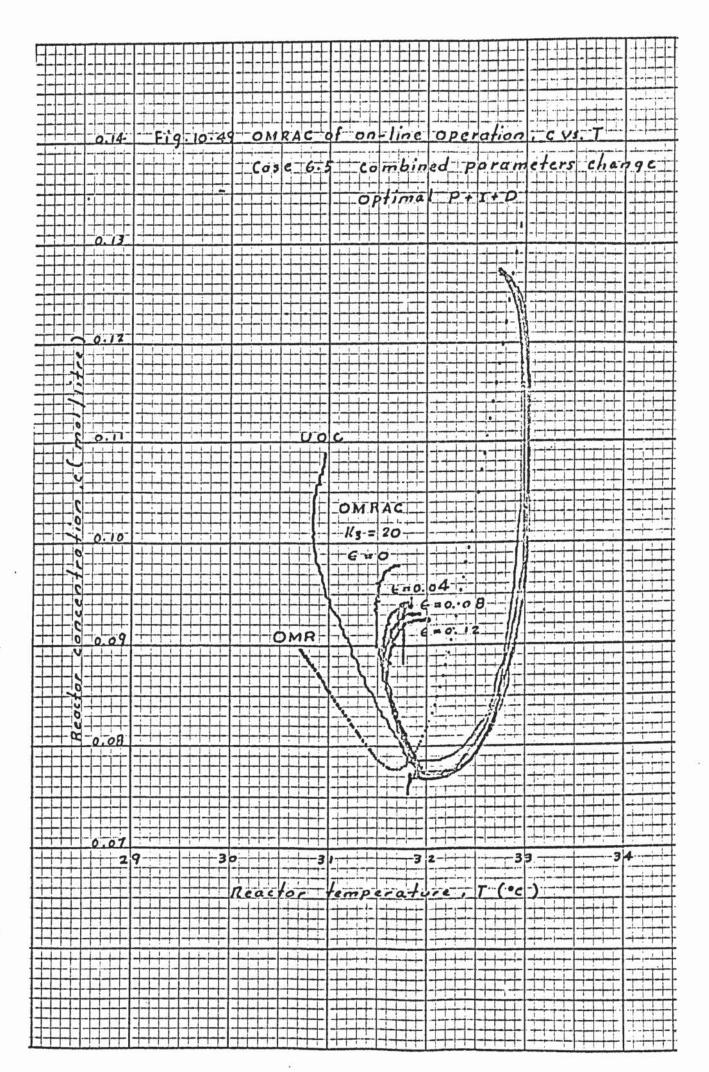
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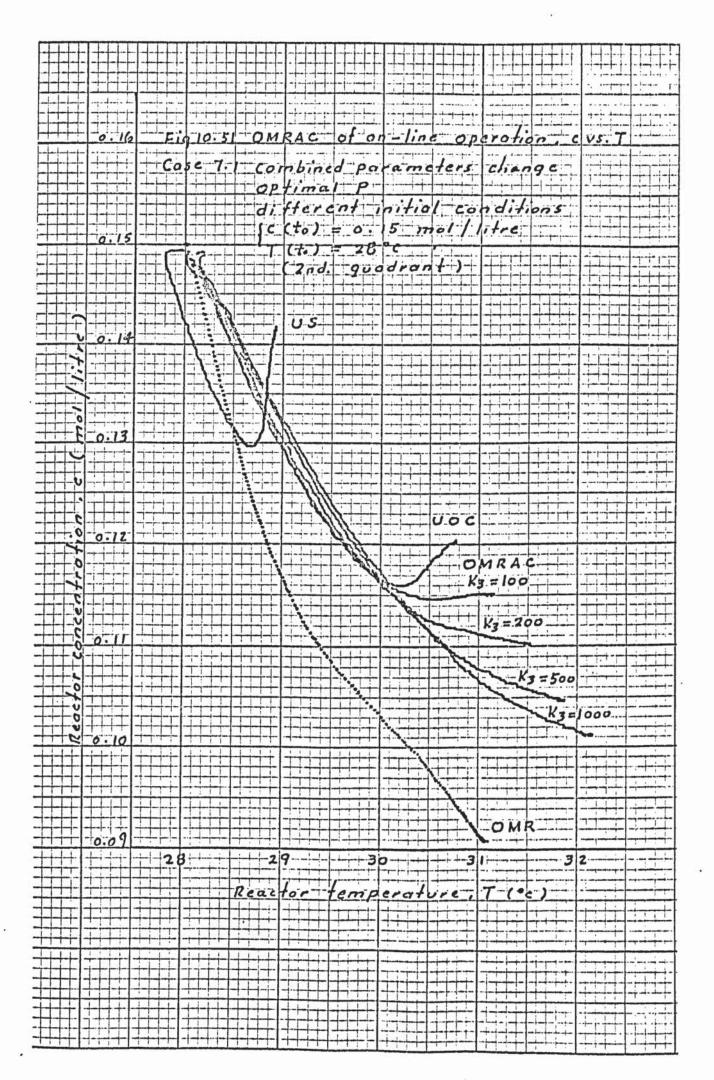
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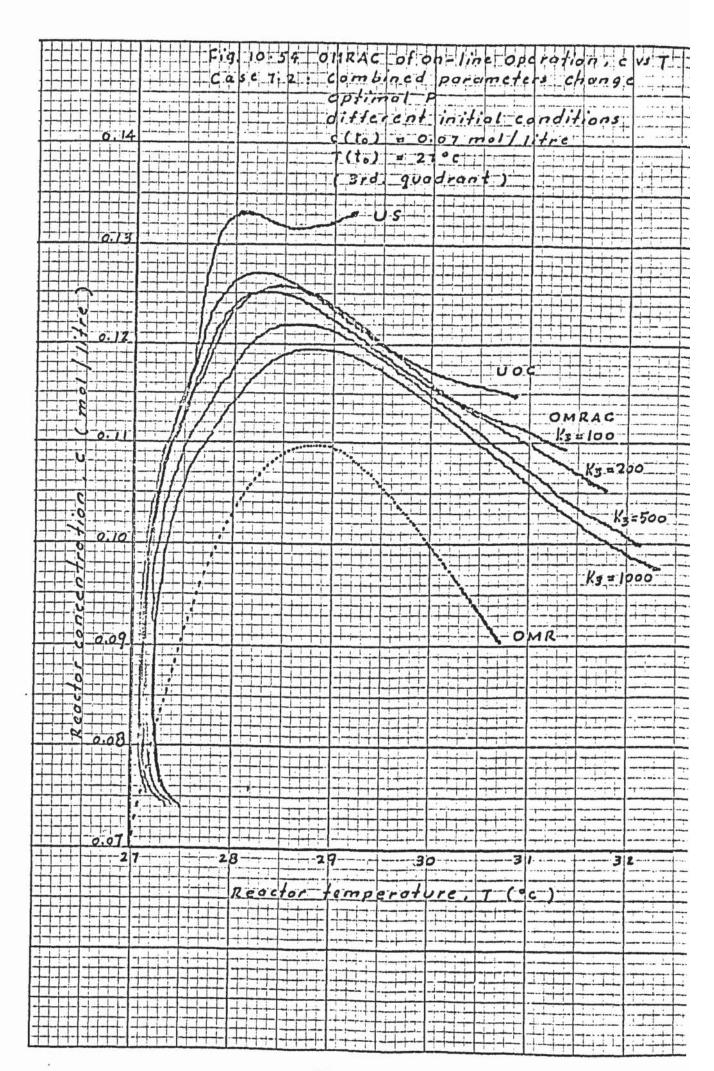
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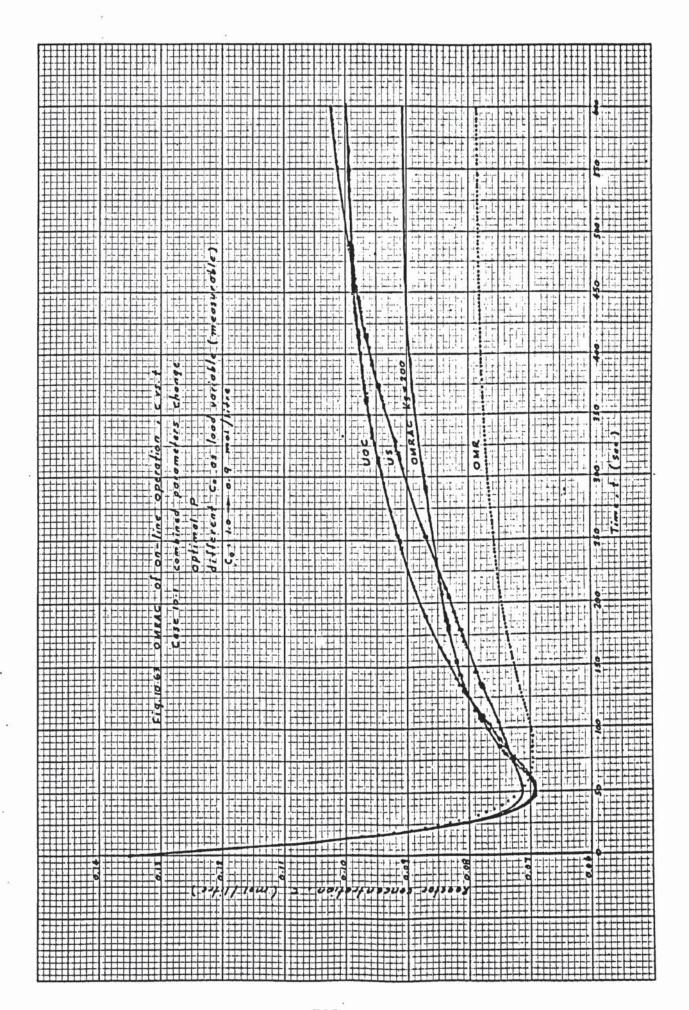
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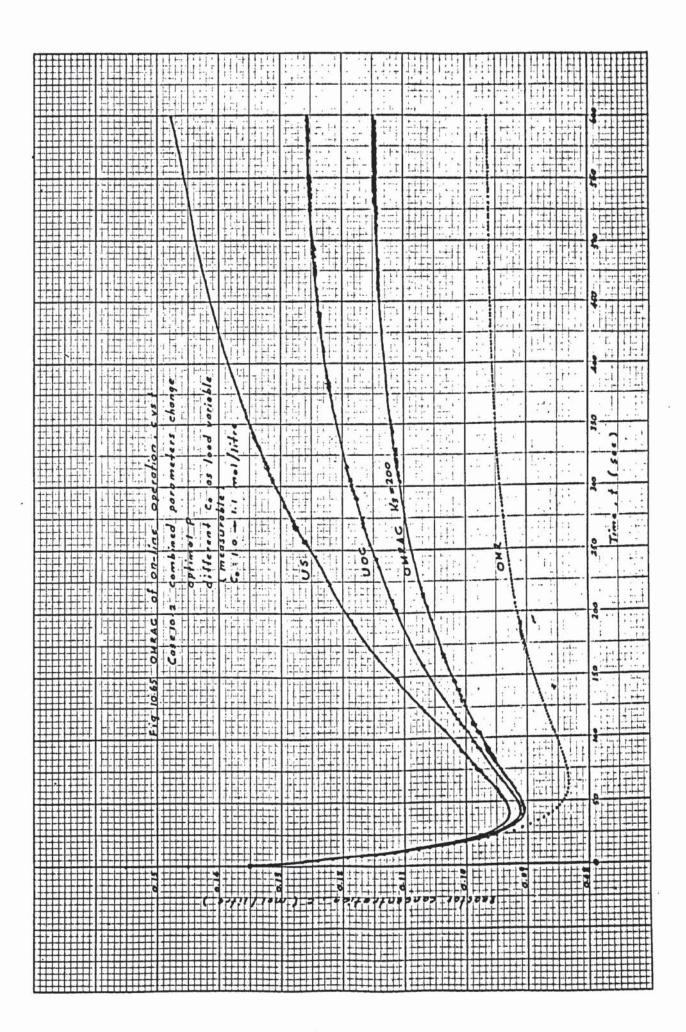
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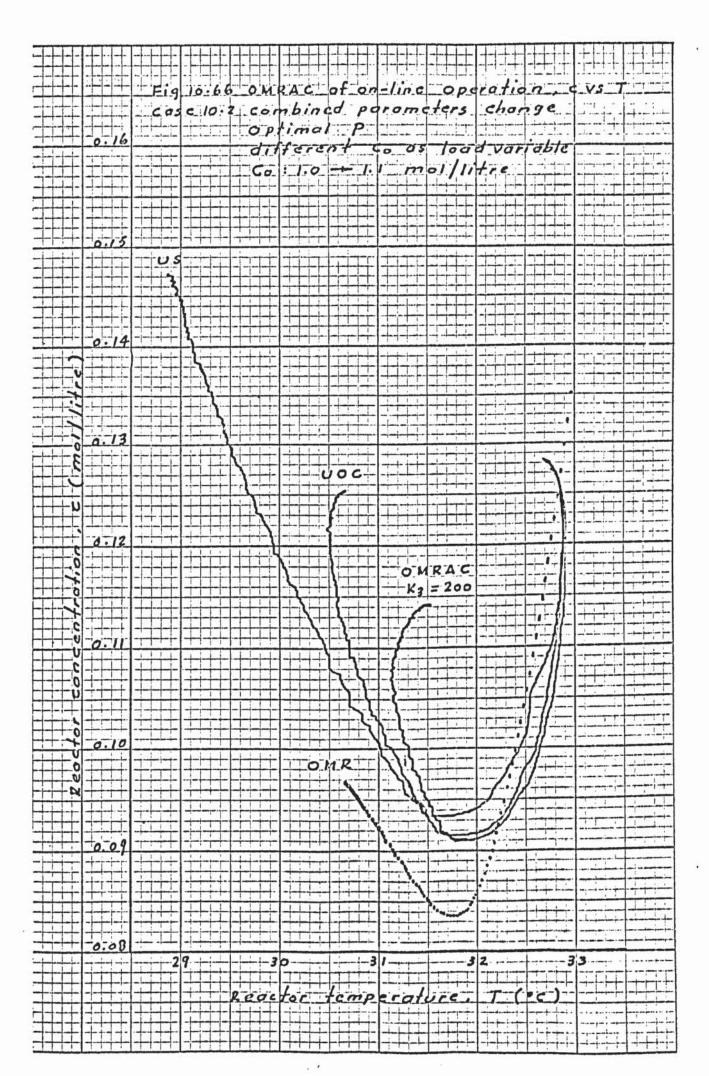
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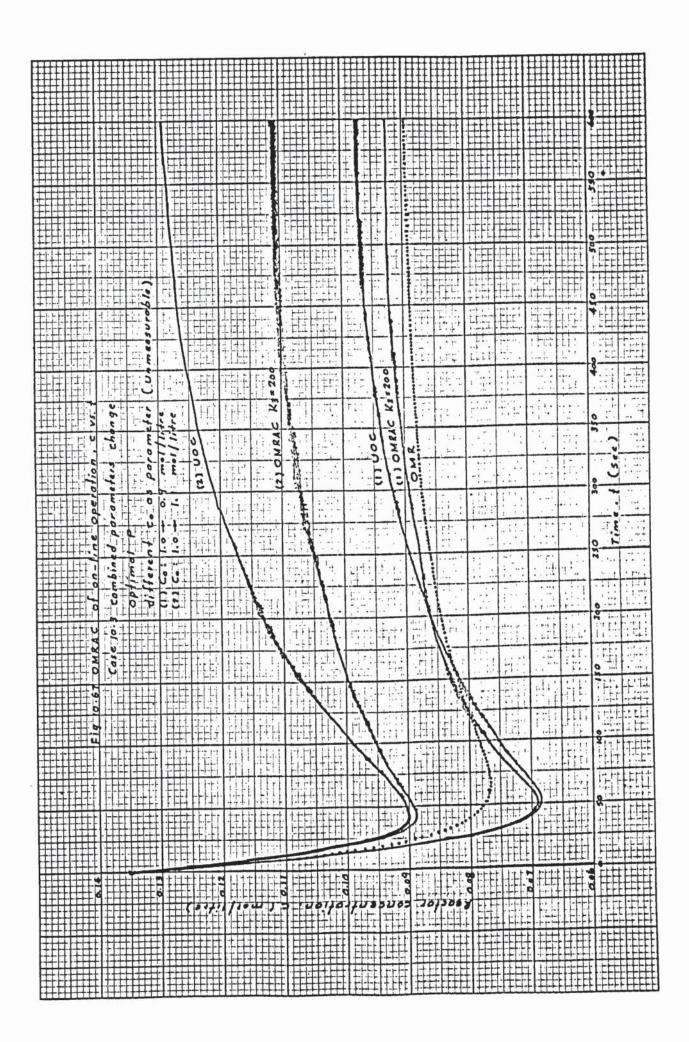


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CHAPTER 11

OPTIMAL ADAPTIVITY

11.1. Definition

All analysis and discussion of OMRAC both for complete simulation (Chapter 7) and on-line operation (Chapter 10) is directly based on the plotter response figures. Now for a fundamental and quantitative analysis and evaluation of OMRAC a new term "Optimal Adaptivity" is introduced and defined as follows:

where
$$\int_{0}^{t_{f}} e^{2}(t)dt = Performance response, \left(\frac{mol}{litre}\right)^{2}(sec)$$

$$e(t) = \left(\mathbf{e}_{1}^{r}(t) - \mathbf{e}_{1}(t)\right)$$

$$= \left(\mathbf{c}_{r}(t) - \mathbf{c}(t)\right) \frac{mol}{litre}$$

UOC = Unadapted optimal control

and MRAC = Model reference adaptive control which
in this research is OMRAC

From the definition, optimal adaptivity can be used as a general term to evaluate any kind of model reference adaptive control.

By using calculated optimal adaptivity with performance response and different weighting factors (K₃) of OAC, a set of three dimensional figures both for complete simulation and for on-line operation of OMRAC can be drawn to show the overall perspective picture of the whole OMRAC system.

11.2. Optimal adaptivity of complete simulation

From Appendix 4, Figs. A.4.1. to A.4.21 obtained by the X-Y plotter, the values of optimal adaptivity for all the different cases can be calculated and are shown in Appendix 7, Tables A.7.1. to A.7.5. and the corresponding optimal adaptivity figures are drawn and shown in Figs. 11.1 to 11.8.

11.3. Optimal adaptivity of on-line operation

Performance response for on-line operation is calculated directly from all dynamic response figures by using a planimeter; the method of calculation is shown in Appendix 7.6.

The values of calculated optimal adaptivity for all the different cases of on-line operation are shown in Appendix 7, Tables A.7.6 to A.7.18, and the corresponding optimal adaptivity figures are drawn and shown in Figs. 11.9 to 11.16.

11.4. Analysis and discussion

- 11.4.1. From the two sets of eight optimal adaptivity figures, the overall perspective figures of the OMRAC system both for complete simulation (theoretical) and on-line operation (practical) are clearly shown to be in good agreement.
- 11.4.2. The optimal adaptivity always increases from ψ \Longrightarrow 50% up to ψ \Longrightarrow 95% as K₃ increases from 100 to 1000. (In case 1.3 where K₃ = 4000 for on-line operation optimal adaptivity is higher at 98.43%).
- 11.4.3. The optimal adaptivity for optimal P + I is much higher than for optimal P alone:

$$\Psi = 95\%$$
 ($\epsilon = 1.0$) $\Psi = 50\%$ ($\epsilon = 0$)

(Optimal P + I) (Optimal P)

11.4.4. The optimal adaptivity optimal P + I + D is much higher than optimal P + D:

$$\psi \triangleq 90\%$$
 ($\varepsilon = 0.12$) $\psi \triangleq 50\%$ ($\varepsilon = 0$)
(Optimal P + I + D) (Optimal P + D)

- 11.4.5. The optimal adaptivity for a constant weighting factor (K_3) of the OAC scheme increases when K_1 and K_2 , the weighting factors, of the OMR scheme, decreases.
- 11.4.6. The optimal adaptivity for different set-point changes (or desired steady state reactor concentration) is approximately the same for complete simulation and on-line operation. Thus:

 $\Psi \implies$ 66% in complete simulation $\Psi \implies$ 60% to 75% in on-line operation. So, optimal adaptivity of OMRAC is independent of the

different set-point changes.

11.4.7. The optimal adaptivity for different inlet concentration changes is also approximately the same, or

 Ψ $\stackrel{\frown}{=}$ 66% in complete simulation

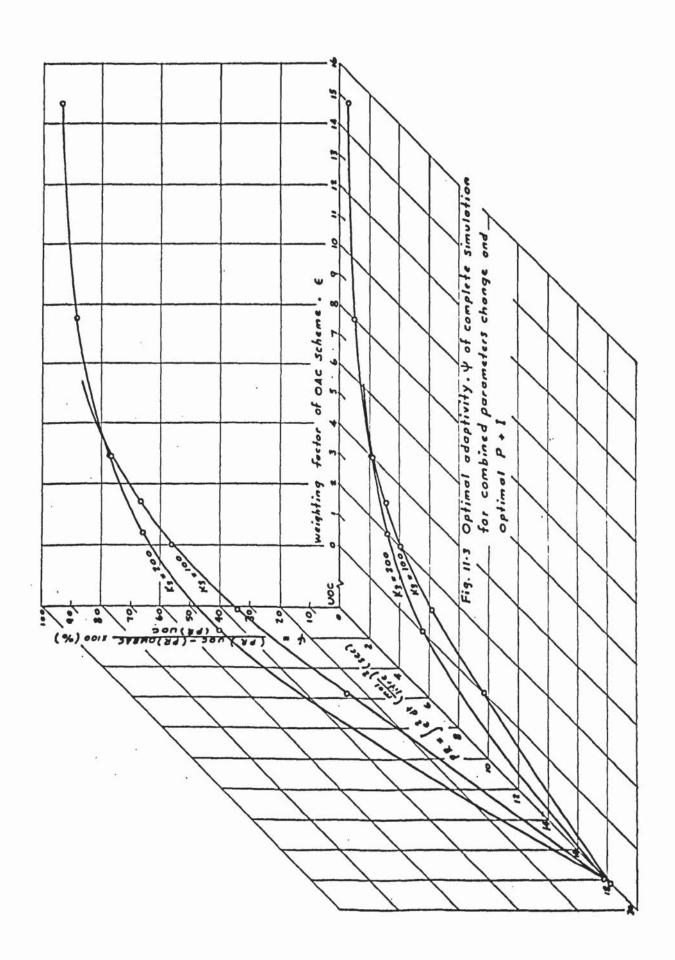
 Ψ \longrightarrow 55% - 70% in on-line operation.

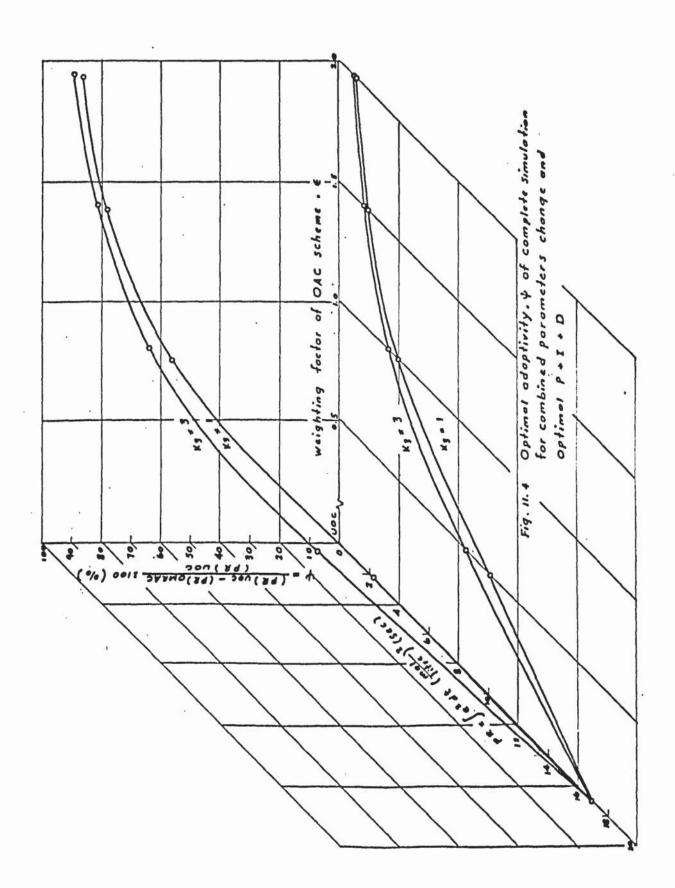
So, optimal adaptivity of OMRAC is independent of the different inlet concentration changes.

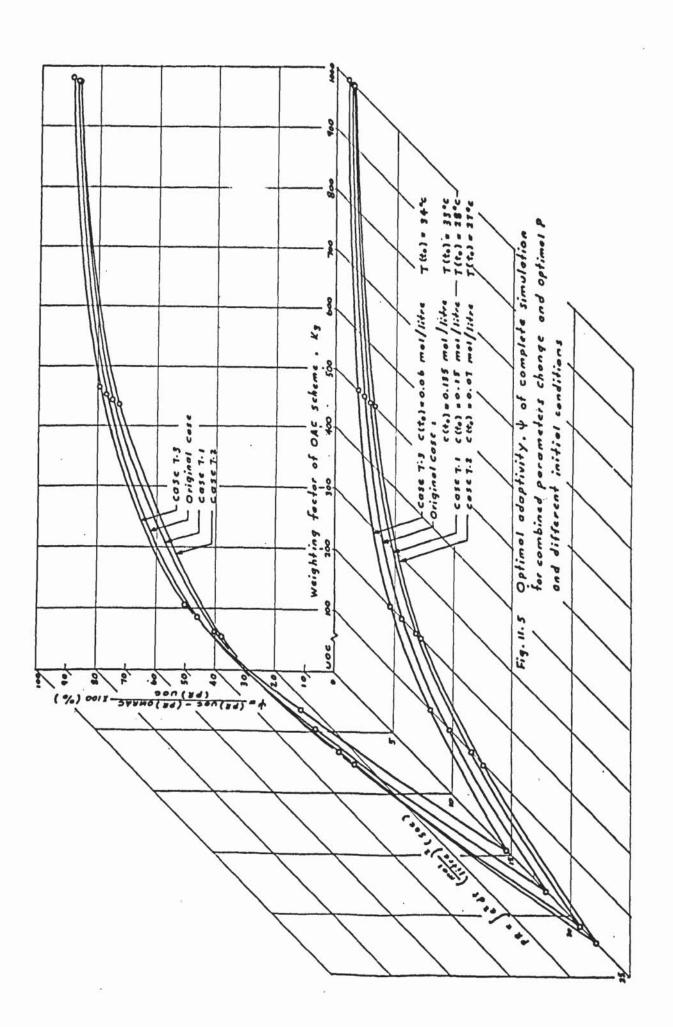
11.4.8. From the above discussion and analysis, the theoretical development of OMRAC has been well established and proved with high performance both in theoretical complete simulation and in practical on-line simulation.

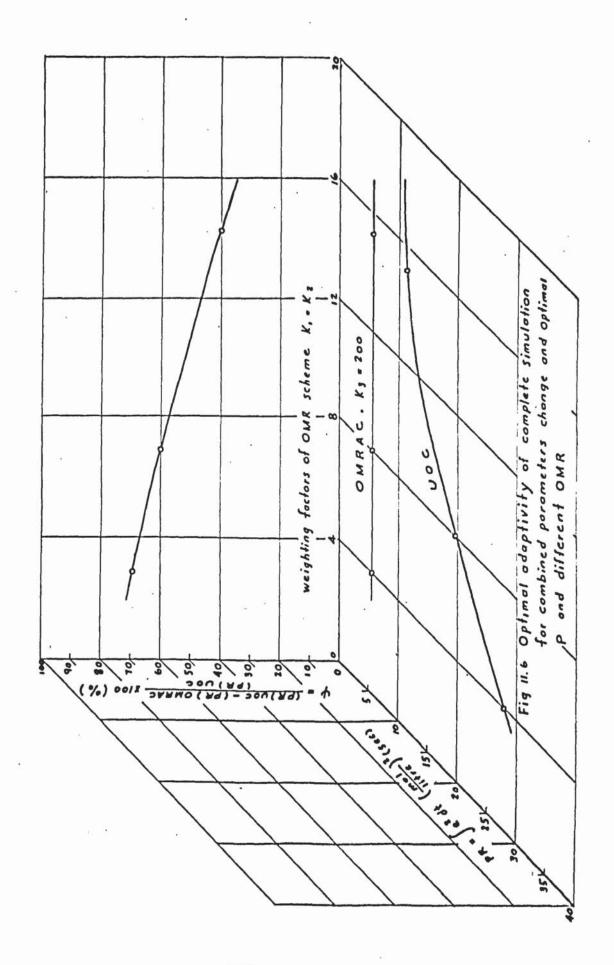
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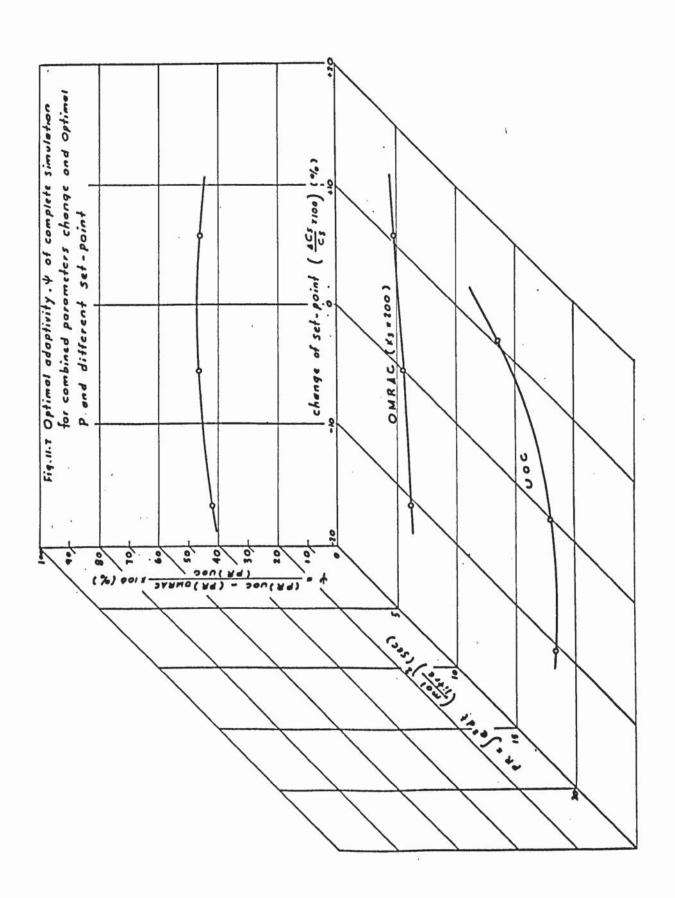
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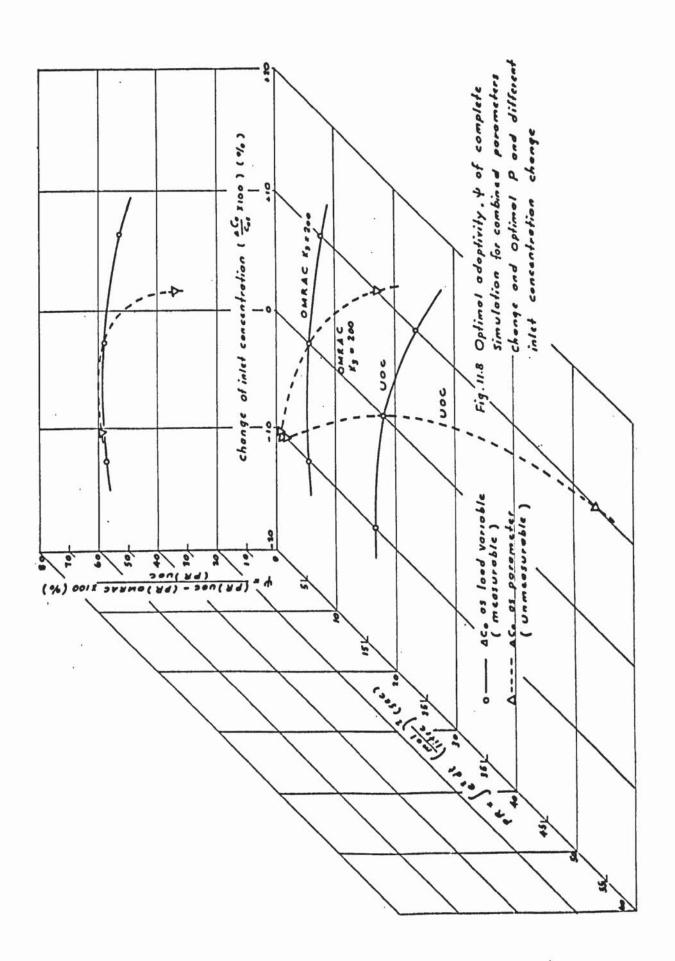


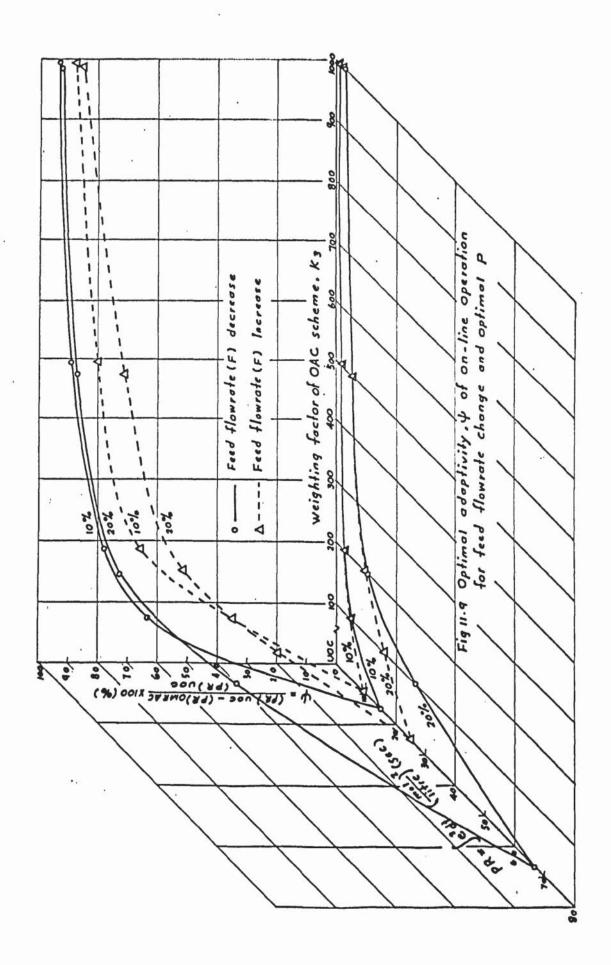




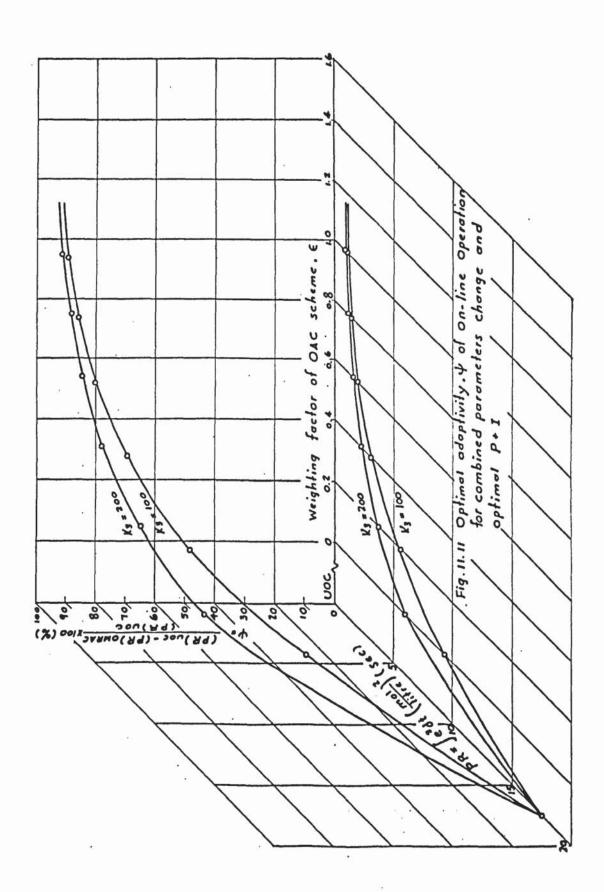


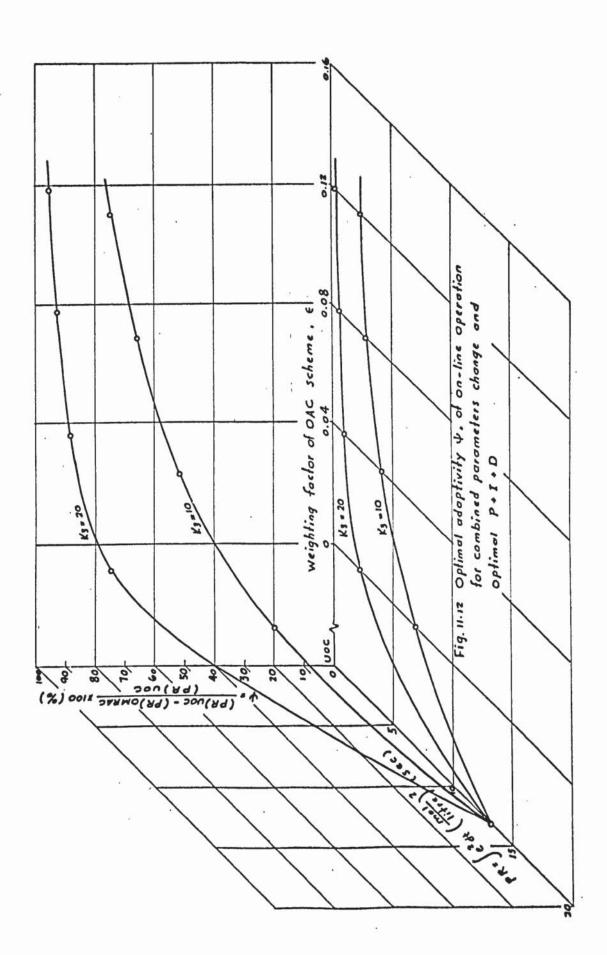


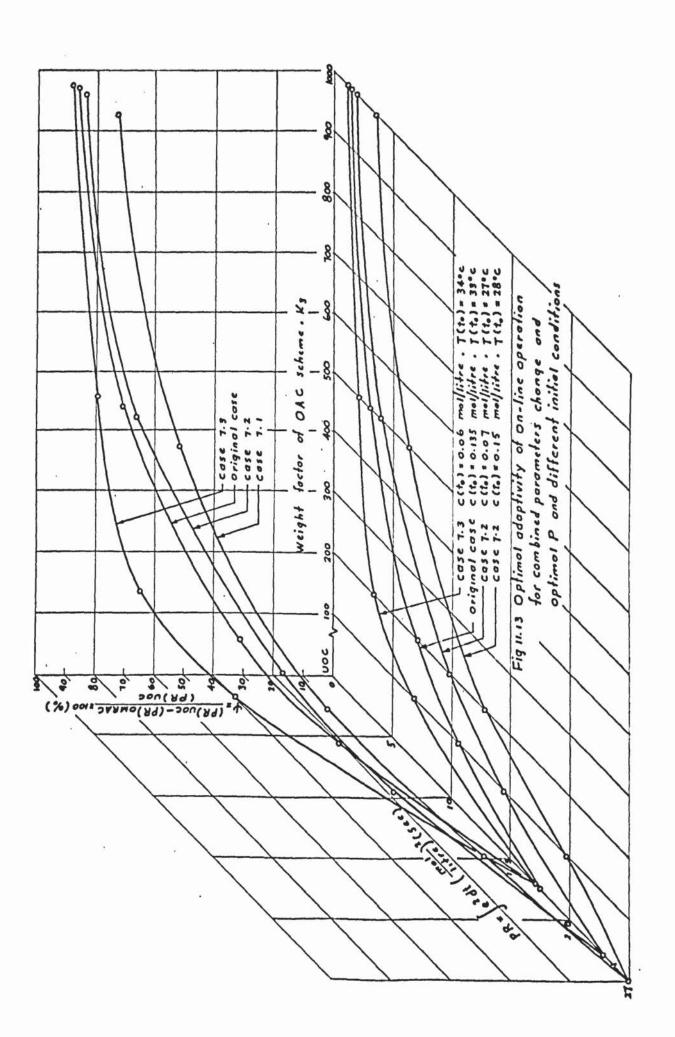


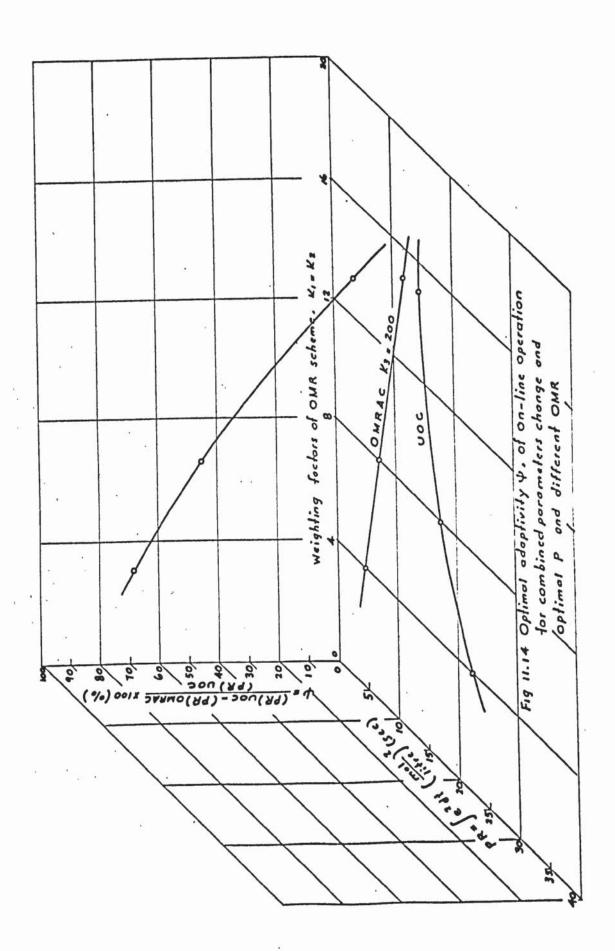


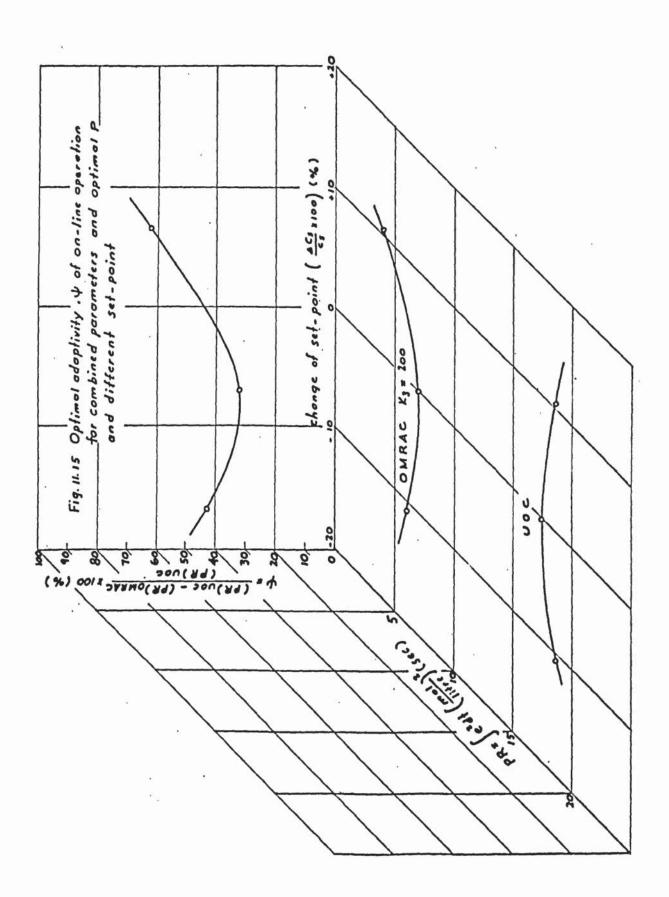
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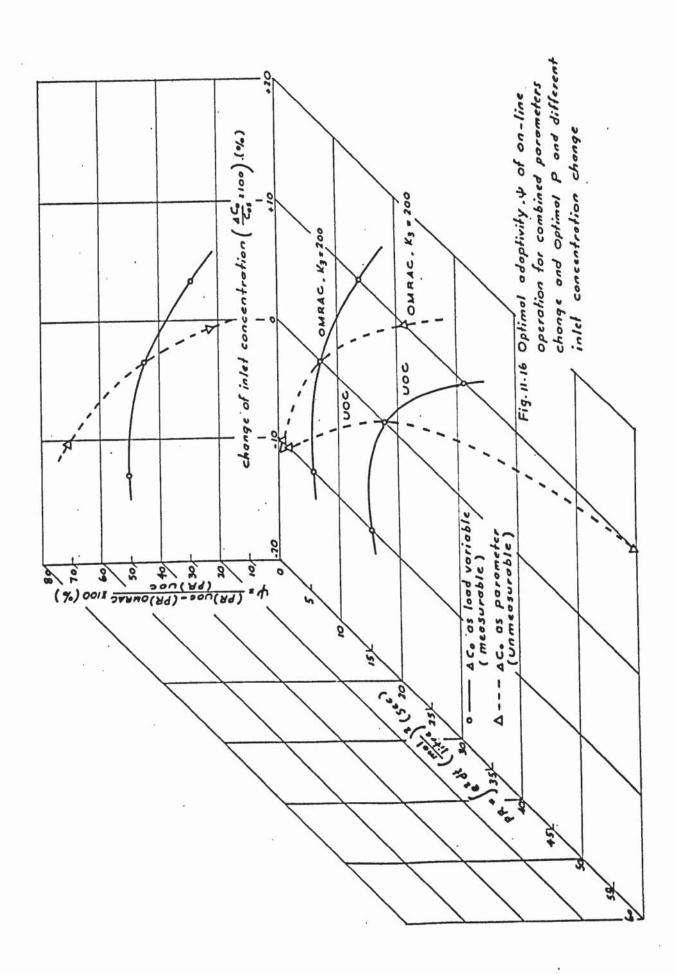












CHAPTER 12

CONCLUSIONS

From all of the analysis and discussion of the different chapters, the overall conclusions are in the following two sections:

12.1. Overall conclusion for OMRAC system

12.1.1. Theoretical development

- (1) A general algorithm and theory of the OMRAC system for an n-state variable process is developed theoretically (3.1).
- (2) The general optimal PID control laws of the OAC scheme are derived in detail. (Chapter 3).
- (3) All the mathematically derived equations of optimal PID control laws for a CSTR are special cases of the general equations (Chapters 4 and 5).

12.1.2. Theoretical and experimental proof

From Chapters 7, 10 and 11, all theoretical and experimental results both from complete simulation and on-line operation for a CSTR using the TR-10 analogue and the TR-48 hybrid computer are apparently in excellent agreement and are shown below:

- (1) The response of OMRAC is always better than UOC and is more effective and approaches OMR more closely as a limit as the weighting factor of OAC is increased.
- (2) The adaptation of OMRAC has no limitation for any operating conditions. The only limitation is the constraint of the optimal control law which corresponds to the control valve capacity for the cooling water flowrate.

- (3) The response of reactor concentration and cooling water flowrate from on-line operation are more sensitive than the theoretical response from complete simulation.
- (4) Optimal P + I and Optimal P + I + D of OMRAC can produce greater improvement than optimal P only, and Optimal PID has the same general properties as the conventional PID controller.
 - (5) Optimal PID control of on-line operation is more sensitive than complete simulation, the best value of the ratio of the two weighting factors (K_3/ϵ) is around 80-100.
 - (6) The stability of OMRAC is asymptotic stability in the large and is much better than the stability of UOC.
 - (7) Q and (-ΔH) calculated from all of the experimental data at the final steady state conditions of on-line operation are in excellent agreement with operating cases and with the originally calculated theoretical values (7.1)
 - (8) Optimal adaptivity for a constant weighting factor (K₃) of the OAC scheme, increases when K₁ and K₂, the weighting factors of the OMR scheme, decrease.
 - (9) Optimal adaptivity of OMRAC is independent of the different set-point changes.
- (10) Optimal adaptivity of OMRAC is independent of the different inlet concentration changes.

From the above analysis the theoretical development of OMRAC has been confirmed and proved to have high performance both from the theoretical complete simulation and experimental on-line operation for a CSTR using a hybrid computer.

12.2. Overall conclusions for on-line computer control system design and operation

From 12.1. On line computer control system design and operation are successful with high performance in the following conditions:

12.2.1. Effective programming of the computer

Effective programming procedures were carefully followed and are shown below:

- (1) Between the computer and interface, all process variables of each computer circuit diagram must be changed to scaled computer variables (Figs. 7.1 and 7.2. and Figs. 8.6 to 8.8)
- (2) Careful consideration of magnitude scaling and timescaling (7.2)
- (3) Careful change of all process and related equations to the scaled computer variable equations (7.3).
- (4) Careful programming of all of the necessary VDFG's (Appendix 3).
- (5) Preparation of detailed assignment sheets for all potentiometers and amplifiers used for each computer diagram (Tables 7.2 to 7.7.).
- (6) Careful determination of the exact relation of each interface variable on the computer side to that on the real process side, for example

$$\left[\frac{Q_g}{Q_{gm}}\right] \text{ in volts to } Q_g \text{ in Kcal x } 10^3/\text{h}$$
 and
$$\left[\frac{U^*}{Q_{cm}}\right] \text{ in volts to } F_c \text{ in litre/min}$$
 where $U^* = \text{modified optimal control law in Kcal/min.}$ (8.33 and 8.3.4.).

(7) Application of simple rules for patching and checking the connection of the two available computers (TR-10 and TR-48) (9.2).

12.2.2. Extremely linear interface system design

In 8.2, it has been emphasised that the requirement of interface system design, as for any industrial transmitter or transducer, is that the terminal relation between the computer side and the process side must be extremely linear. To meet this requirement, an additional compensating VDFG is used, and the design procedures are shown below:

- (1) Prepare complete block diagram of each individual component of interface system.
- (2) Calibrate and check each block function.
- (3) Combine all components of each block function to form an overall resultant function for the interface system (usually this is non-linear).
- (4) From the resultant non-linear function, an additional compensating VDFG is used to compensate for the non-linearity to give an extremely linear function.

Thus, the signal from the computer is transmitted through the generated VDFG and then a series of monitoring instruments and items of equipment, give an excellent linear interface system.

(8.2.1. and 8.2.2. and Appendix 5).

12.2.3. High sensitivity of on-line operation.

Since the overall sensitivity in this research work is 50 times that of Buxton's (see 9.1.) then several serious difficulties of operation on the partially simulated CSTR had

to be solved and are shown below:

- (1) Smooth plot of oscillating or fluctuating reactor temperature using a filter technique (see 9.3).
- (2) Initial temperature setting using a switching method (see 9.4).
- (3) Determination of the actual cooling water flowrate at the final steady state or $\left\lceil \frac{F_{cs}}{F_{cm}} \right\rceil$, by using an iteration method (9.5).
- (4) Changing the feed flowrate (F), as an unmeasurable parameter, using a compensation method (9.6).

Since a very narrow operating range both for reactor concentration and temperature was used on the partially simulated CSTR, the highly sensitive performance of different types of on-line operations such as UC, UOC, OMRAC and OMR of a CSTR were plotted respectively in all Figures (Figs. 10.1 to 10.68) for comparison with the theoretical results.

Thus the partial simulation technique has been extended to give a more highly sensitive operating performance than Buxton's original design by use of a compensation technique combined with switching and iteration methods.

In the application of optimal control theory (including OMRAC) to practical real processes, Shimner (14) clearly pointed out that the optimal control theory represents an important area of research in the control field. Unfortunately a large gap has developed between research in academic and industrial organisations, i.e. between research and practice and very little has been converted into practice. This gap will undoubtedly shrink in the very near future, and the discussion (2.6.1) of Literature Survey (Chapter 2) emphasises this fact.

In a broad sense, the major effort of this research may contribute to the filling of this gap between research and practice of optimal control theory (including OMRAC).

12.3. Suggestion for future work

A proposed comparison of OMRAC for a CSTR using the on-line hybrid computer with the theoretical development of OMRAC is shown in Table 12.1.

Table 12.1

Comparison of theoretical development and .

application of OMRAC.

	Theoretical development of OMRAC	Application of OMRAC for a CSTR
1. Process	N-state variables (N-1) controlled variables	2-state variables 1-controlled var- iable (Reactor concentration)
2. Process equipment	Any type, either partially simulated or real process equipment	partially simulated CSTR
 Optimal control techniques 	Any kind of optimal control technique	maximum principle
4. On-line computer	any type of on-line hybrid or digital combined computer	TR-10 and TR-48 hybrid computers

From the above Table, for different processes with either partially simulated or real process equipment, applying different kinds of optimal control technique and using different types of on-line computer then new research on the OMRAC scheme may be developed with a sound foundation. For example: using the existing Departmental equipment, the following particular kind of OMRAC research is suggested:

"Optimal Model Reference Adaptive Control of a Cascaded twoeffect evaporator using on-line Honeywell Digital Computer."

APPENDICES

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(with index)

APPENDICES

		Page
Appendix 1.	Digital computer computation of the optimal control law coefficients a ij and β_{ij} by the Newton-Raphson	
37	iteration method	
Al.1	General iteration algorithm	363
A1.2	Determination of the coefficients 12, 422, 423, 424 and 425 (OMR scheme)	365
A1.3	Determination of the coefficient $m{\beta}_{12}$ (Optimal P of OAC scheme)	368
Al.4	Determination of the coefficients β_{21} and β_{26} (Optimal P + I of OAC scheme)	369
A1.5	Determination of the coefficients β_{21} , β_{26} and β_{27} (Optimal P + I + D of OAC scheme)	371
Appendix 2.	Digital computer programming	
A2.1	Computer programming - 1 (based on Al.2)	375
A2.2	Computer programming - 2 (based on Al.3)	378
A2.3	Computer programming - 3 (based on Al-4)	380
A2.4	Computer programming - 4 (based on Al.5)	382
A2.5	Computer programming - 5 Calculation of velocity constant from the Arrhenius equation T vs k.	386
A2.6	Computer programming - 6 Calculation of velocity constant from the Arrhenius equation $T \ vs \left[\begin{array}{c} \frac{T}{T_m} \end{array} \right] \ and \left[\begin{array}{c} \frac{K}{K_m} \end{array} \right]$	336
A2.7	Tables of computed a ij and B ij values. (Tables A.2.1 to A.2.4)	407 to 301

Appendix 3.	VDFG generation figures	
	Figures A.3.1 to A.3.3.	392 to 394
Appendix 4.	Performance response figures of complete simulation	
ā	Figures A.4.1. to A.4.21	395to 415
Appendix 5.	Calibration of monitoring equipment and instruments	
	Tables and corresponding Figures of calibration data:	
	Tables A.5.1 to A.5.16	416 to 429
	Figures A.5.1 to A.5.19	430 to 448
Appendix 6.	Experimental data at final steady state of on-line operation	
	Tables A.6.1 to A.6.10	449 to 458
8 9 F	29	
Appendix 7.	Optimal adaptivity calculation	
A7.1	Optimal adaptivity of complete simulation	
WI V	Tables A.7.1. to A.7.5.	459 to 466
A7.2	Performance response calculation from dynamic response figures of on-line operation	467 to 469
A7.3	Optimal adaptivity of on-line operation	
* •	Tables A.7.6. to A.7.18	470 to 482

INDEX TO TABLES IN THE APPENDICES

Table No.	Title	Page
A.2.1.	values of OMR scheme computed from A.2.1.	387
A.2.2	\$ 12 value of OAC scheme for Optimal P computed from A2.2	38 7
A.2.3.	<pre>B ij value of OAC scheme for Optimal P + I control computed from A2.3</pre>	388 - 389
A.2.4.	<pre>B_{ij} values of OAC scheme for Optimal P + I + D control computed from A2.4</pre>	390 - 391
A.5.1.	Calibration of feed flowrate (F) rotameter	416
A.5.2.	Calibration of cooling water flowrate (F_c) rotameter.	417
A.5.3.	Calibration of flowmeter transmitter	418
A.5.4.	Calibration of thermocouples	418
A.5.5.	Calibration of temperature transmitters	419
A.5.6.	Calibration of voltage to current (V/I) converter	419
A.5.7.	Calibration of current to pneumatic pressure (I/P) transducer	420
A.5.8.	Calibration of combined V/I converter and I/P transducer	421
A.5.9.	Calibration of control valve flowrate vs pneumatic pressure (without positioner)	422
A.5.10.	Calibration of control valve positioner	423
A.5.11.	Calibration of control valve flowrate vs pneumatic pressure (with positioner)	424
A.5.12.	Calibration of V/I converter input from TR-48 (volt) vs control valve flowrate (litre/min) (with positioner)	425

Table No.	Title	Pago
A.5.13.	Calibration of overall F interface	
	system between $\left[\frac{F_c}{F_{cm}}\right]$ (volt) from	
w V	hybrid computer and F _c (litre/min)	1-6
	from control valve (with positioner)	426
A.5.14.	Calibration of computer output $\left[\begin{array}{c} Q_{gg} \\ Q_{gm} \end{array} \right]$	
	vs variac position.	427
A.5.15.	Calibration of variac position vs heat output from immersion heater, Q_g	428
A.5.16.	Calibration of overall heat generation Q interface system between	
	$\left[\begin{array}{c} Q_g \\ \overline{Q_{gm}} \end{array}\right]$ (before DFG) vs Q_g (from	
(a):	immersion heater)	429
A.6.1.	Final steady state conditions of on-line operation for Cases 1.1 and	
	1.2.	449
A.6.2.	Final steady state conditions of on-line operation for Cases 1.3 and 1.4	450
A.6.3.	Final steady state conditions of on-line operation for Cases 2.1, 2.2, and 2.3.	451
A.6.4.	Final steady state conditions of	
8 - 42	on-line operation for Cases 3.1, 3.2 and 3.3.	452
A.6.5.	Final steady state conditions of on-line operation for cases 4.1 and	
	4.2.	453
A.6.6.	Final steady state conditions of on-line operation for Cases 5.1, 5.2	
. ×	and 5.3.	454
A.6.7.	Final steady state conditions of on-line operations for Cases 6.1, 6.3	
	and 6.5	455
A.6.8.	Final steady state conditions of on-line operation for Cases 7.1, 7.2	
	and 7.3.	456

Table No.	Title	Pago
A.6.9.	Final steady state conditions of on-line operation for Cases 3.1 and 9.1.	457
A.6.10.	Final steady state conditions of on-line operation for Cases 10.1, 10.2 and 10.3.	458
A.7.1.	Optimal adaptivity of complete simulation for Cases 1.1, 1.2, 1.3 and 1.4.	459
A.7.2.	Optimal adaptivity of complete simulation for cases 2.1, 2.2, 3.1, 3.2 and 3.3.	460-461
A.7.3.	Optimal adaptivity of complete simulation for Cases 4.1, 5.1 and 5.2.	462
A.7.4.	Optimal adaptivity of complete simulation for Cases 6.1, 6.2, 7.1, 7.2 and 7.3.	463-464
A.7.5.	Optimal adaptivity of complete simulation for cases 8.1, 9.1, 10.1 and 10.2.	465-466
A.7.6.	Optimal adaptivity of on-line operation for Cases 1.1 and 1.2.	470
A.7.7.	Optimal adaptivity of on-line operation for Cases 1.3 and 1.4.	471
A.7.8.	Optimal adaptivity of on-line operation for Cases 2.1 and 2.2.	472
A.7.9.	Optimal adaptivity of on-line operation for Cases 2.3. and 3.1.	473
A.7.10.	Optimal adaptivity of on-line operation For cases 3.2. and 3.3.	474
A.7.11.	Optimal adaptivity of on-line operation for Cases 4.1 and 4.2.	475
A.7.12.	Optimal adaptivity of on-line operation for Cases 5.1 and 5.2.	476
A.7.13.	Optimal adaptivity of on-line operation for Cases 5.3 and 6.1.	477
A.7.14.	Optimal adaptivity of on-line operation for Cases 6.2 and 6.3.	478
100		

Table No.	Title	Page
A.7.15.	Optimal adaptivity of on-line operation for Cases 7.1 and 7.2.	479
A.7.16.	Optimal adaptivity of on-line operation for Cases 7.3 and 8.1.	480
A.7.17.	Optimal adaptivity of on-line operation for Cases 9.1 and 10.1.	481
A.7.18.	Optimal adaptivity of on-line operation for Cases 10.2 and 10.3.	482

INDEX TO FIGURES IN THE APPENDICES

Figure No.	Title	Page
A.3.1.	VDFG-1 and VDFG-2 generation curves $\left[\begin{array}{c} \frac{T}{T_m} \end{array}\right]$ vs $\left[\begin{array}{c} \frac{K}{K_m} \end{array}\right]$ (both for OMR scheme and OAC scheme)	392
A.3.2.	$\begin{bmatrix} VDFG-3 & generation & curve \\ \frac{F}{F_{cm}} \end{bmatrix} vs \begin{bmatrix} \frac{F_{cg}}{F_{cm}} \end{bmatrix}$	393
A.3.3.	DFG-4 generation curve $\left[\begin{array}{c} \frac{Q_g}{Q_{gm}} \end{array}\right] vs \left[\begin{array}{c} \frac{Q_{gg}}{Q_{cm}} \end{array}\right] \text{ (on TR-10)}$	394
	Performance responses of complete simulation for:	
A.4.1.	Case 1.1.	395
A.4.2.	Case 1.2.	396
A.4.3.	Case 1.3.	397
A.4.4.	Case 1.4.	398
A.4.5.	Case 2.1.	399
A.4.6.	Case 2.2.	400
A.4.7.	Case 3.1.	401
A.4.8	Case 3.2.	402
A.4.9.	Case 3.3.	403
A.4.10.	Case 4.1.	404
A.4.11.	Case 5.1.	405
A.4.12.	Case 5.2.	406
A.4.13.	Case 6.1.	407
A.4.14.	Case 6.2.	408
A.4.15.	Case 7.1.	409
A.4.16.	Case 7.2.	410
A.4.17.	Case 7.3.	411
A.4.18.	Case 8.1.	412

Figure No.	Title	Page
A.4.19.	Case 9.1.	413
A.4.20.	Case 10.1.	414
A.4.21.	Case 10.2.	415
A.5.1.	Calibration of feed flowrate (F) rotameter	430
A.5.2.	Calibration of cooling water flowrate (F _c) rotameter	431
A.5.3.	Calibration of flowmeter transmitter	432
A.5.4.	Calibration of thermocouples	433
A.5.5.	Calibration of temperature Transmitters	434
A.5.6.	Calibration of voltage to current (V/I) converter	435
A.5.7.	Calibration of current to pneumatic pressure (I/P) transducer	436
A.5.8.	Calibration of combined V/I converter and I/P transducer	437
A.5.9.	Calibration of control valve flowrate vs pneumatic pressure (without positioner)	438
A.5.10.	Calibration of control valve positioner	439
A.5.11.	Calibration of control valve flowrate vs pneumatic pressure (with positioner)	440
A.5.12	Calibration of V/I converter input from TR-48, $\left[\frac{F_{cg}}{F_{cm}}\right]$ (volts) vs control valve	441
	flowrate, F _c (litre/min) with positioner	
A.5.13.	Compensation curve of F_c interface system on VDFG, $\left[\frac{F_c}{F_{cm}}\right]$ vs $\left[\frac{F_{cg}}{F_{cm}}\right]$	442
A.5.14.	Calibration of overall F_c interface system between $\left[\frac{F_c}{F_{cm}}\right]$ (volt) from	
	hybrid computer and F _c (litre/min)	
	from control valve (with positioner)	443

Figure No.	Title	Page
A.5.15.	Calibration of computer output $\left[\begin{array}{c} Q_{gg} \\ Q_{gm} \end{array}\right]$ vs variac position	444
A.5.16.	Calibration of variac position vs heat output from immersion heater, Q_g .	445
A.5.17.	Calibration of computer output $ \left[\begin{array}{c} \frac{Q_{gg}}{Q_{gm}} \end{array}\right] \text{vs heat output from immersion} $ heater, Q_g .	446
A.5.18.	Compensation curve of Q_g interface system on VDFG: $ \left[\begin{array}{c} Q_g \\ \overline{Q}_{gm} \end{array} \right] \ \text{vs} \left[\begin{array}{c} Q_{gg} \\ \overline{Q}_{gm} \end{array} \right] $	447
A.5.19.	Calibration of overall heat generation interface system between $\left[\begin{array}{c}Q_g\\Q_{gm}\end{array}\right]$ (before VDFG) vs Q (from immersion heater.	448
A.7.1.	Performance response calculation from dynamic response curve	469

APPENDIX 1

DIGITAL COMPUTER COMPUTATION OF THE OPTIMAL CONTROL LAW COEFFICIENTS & AND B ij BY THE

NEWTON RAPHSON ITERATION METHOD

A.1.1. General iteration algorithm

Let the simultaneous non-linear algebraic equations be shown in the following general form:

or in matrix form:

$$F(X) = 0 (7-2)$$

where

$$F = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} \text{ and } X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

If X are the roots of equation (7+2), expansion as a Taylor series gives:

$$F(\overline{X}) = F(X^{(1)}) + \left(\frac{\partial F}{\partial X}\right)_{X = X^{(1)}} (\overline{X} - X^{(1)}) + \dots$$
(7-3)

where:

 $X^{(1)}$ = first approximated value of \overline{X} , or the first iteration

and
$$\frac{\partial F}{\partial x} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \dots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \dots & \frac{\partial f_2}{\partial x_2} \\ \vdots & \vdots & & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \dots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}$$
 (7-4)

This matrix is called the Jacobi matrix.

Neglecting the high order terms, equation (7-3)

becomes:

$$F(\overline{X}) \cong F(X^{(1)}) + \left(\frac{\partial F}{\partial X}\right)_{X = X^{(1)}} (\overline{X} - X^{(1)}) \qquad (7-5)$$

Let the second approximation of \overline{X} be $X^{(2)}$ and let

$$F(X^{(2)}) \cong 0$$
, then

$$x^{(2)} = x^{(1)} - \left[\frac{\partial F}{\partial x}\right]^{-1} F(x^{(1)})$$
 (7-6)

where

$$\left[\begin{array}{c} \frac{\partial F}{\partial X} \end{array}\right]^{-1} \quad \text{is the inverse matrix of the} \\ \qquad \qquad \max \left(\frac{\partial F}{\partial X}\right)_{X = X} (1)$$

The general formula of this iteration algorithm is:

$$X^{(i+1)} = X^{(i)} - \left(\frac{\partial F}{\partial X}\right)^{-1} F(X^{(i)})$$
 (7-7)

where i and i+l are the ith and (i+l)th iterations and $\left(\frac{\partial F}{\partial X}\right)^{-1}$ is the inverse matrix of $\left(\frac{\partial F}{\partial X}\right)_{X=X}$ (i)

For simplification in the digital computer programming,

let:

$$X (I) = X (7-8-1)$$

$$F(J) = F(X) \qquad (7-8-2)$$

$$A \quad (I,J) = \frac{\partial F}{\partial X} \tag{7-8-3}$$

$$B (I,J) = \left(\frac{\partial F}{\partial X}\right)^{-1}$$
and $R (I) = \left(\frac{\partial F}{\partial X}\right)^{-1}$. $F (X) = B (I,J)$. $F (J)$ (7-8-5)
where $I = 1, 2, \dots, n$

$$J = 1, 2, \dots, n$$

n = no. of determined coefficients then equation (7-7) becomes:

$$X^{(i+1)}(I) = X^{(i)}(I) - B^{(i)}(I,J) \cdot F^{(i)}(J)$$
or
 $X^{(i+1)}(I) = X^{(i)}(I) - R^{(i)}(I)$
(7-10)

A.1.2. Digital computer computation for determination of the coefficients α_{12} , α_{22} , α_{23} , α_{24} and α_{25} (OMR) scheme

From Chapter 4, the derived nine simultaneous nonlinear equations $(4-54) \sim (4-62)$ are rewritten below:

$$K_1 + a_{11}a_{11} + a_{21}a_{12} - 0.25 b^2 a_{12}^2 = 0$$
 (7-11)

$$a_{12}d_{11} + (a_{11} + a_{22})d_{12} + a_{21}d_{22} - 0.5 b^2 d_{12}d_{22} = 0$$
 (7-12)

$$-2K_1 + a_{11}\alpha_{13} + a_{21}\alpha_{23} - 0.5 b^2 \alpha_{12}\alpha_{23} = 0 \quad (7-13)$$

$$a_{11}a_{11} + a_{11}a_{14} + a_{21}a_{24} = 0.5 a_{12}a_{24} = 0 (7-14)$$

$$a_{22}a_{12} + a_{11}a_{15} + a_{21}a_{25} - 0.5 a_{12}a_{25} = 0$$
 (7-15)

$$K_2 + a_{12} a_{12} + a_{22} a_{22} - 0.25 b^2 a_{22}^2 = 0 (7-16)$$

$$a_{12}d_{13} + a_{22}d_{23} - 0.5 d_{22}d_{23} = 0$$
 (7-17)

$$a_{11}a_{12} + a_{12}a_{14} + a_{22}a_{24} - 0.5 = 22a_{24} = 0 (7-18)$$

$$a_{12}a_{15} + a_{22}a_{22} + a_{22}a_{25} = 0.5 b^2 a_{22}a_{25} = 0 (7-19)$$

Let
$$x(1) = a_{11}$$
 $x(4) = a_{14}$ $x(7) = a_{23}$ }
 $x(2) = a_{22}$ $x(5) = a_{15}$ $x(8) = a_{24}$ } $(7 - 20)$
 $x(3) = a_{23}$ $x(6) = a_{22}$ $x(9) = a_{25}$ }

$$P(1) = K_1$$
 $P(2) = K_2$ $(7 - 21)$

$$D(1) = a_{11}$$
 $D(5) = b$

$$D(2) = a_{12}$$
 $D(6) = d_{11}$

$$D(3) = a_{21}$$
 $D(7) = d_{22}$ } $(7 - 22)$

$$D(4) = a_{22}$$

and

F(1), F(2),..... F(9) represent the above nine equations respectively.

Then equations (7-11) (7-19) become:

$$F(1) = P(1) + D(1) \times (1) + D(3) \times (2) - 0.25 D^{2}(5) \times^{2} (2)$$
 (7-23)

$$F(2) = D(2) \times (1) + (D(1) + D(4)) \times (2) + D(3) \times (6)$$

$$= 0.5 D^{2}(5) \times (2) \times (6)$$
(7-24)

$$F(3) = 2P(1) + D(1) \times (3) + D(3) \times (7) = 0.5 D^{2}(5) \times (2) \times (7)$$

$$(7-25)$$

$$F(4) = D(6) \times (1) + D(1) \times (4) + D(3) \times (8) - 0.5 D^{2}(5) \times (2) \times (8)$$

(7-26)

$$F(5) = D(7) \times (2) + D(1) \times (5) + D(3) \times (9) - 0.5 D^{2}(5) \times (2) \times (9)$$

$$(7-27)$$

$$F(6) = P(2) + D(2) \times (2) + D(4) \times (6) - 0.25D^{2}(5) \times^{2} (6)$$
 (7-28)

$$F(7) = D(2) \times (3) + D(4) \times (7) - 0.5 D^{2}(5) \times (6) \times (7)$$
 (7-29)

$$F(8) = D(6) \times (2) + D(2) \times (4) + D(4) \times (8) - 0.5 D^{2}(5) \times (6) \times (8)$$

(7-30)

$$F(9) = D(2) \times (5) + D(7) \times (6) + D(4) \times (9) - 0.5 D^{2}(5) \times (6) \times (9)$$
(7-31)

and
$$\frac{\partial F}{\partial X} =$$

$$D(1) \quad D(3) - 0.5 \quad D^{2}(5) \times (2) \quad 0 \quad 0 \quad 0$$

$$D(2) \quad (D(1) + (D(4)) - 0.5 \quad D^{2}(5) \times (6) \quad 0 \quad 0 \quad 0$$

$$0 \quad -0.5 \quad D^{2}(5) \times (7) \quad D(1) \quad 0 \quad 0$$

$$D(6) \quad -0.5 \quad D^{2}(5) \times (8) \quad 0 \quad D(1) \quad 0$$

$$0 \quad D(7) - 0.5 \quad D^{2}(5) \times (9) \quad 0 \quad 0 \quad D(1)$$

$$0 \quad D(2) \quad 0 \quad 0 \quad D(2) \quad 0 \quad 0$$

$$0 \quad D(2) \quad 0 \quad 0 \quad D(2) \quad 0 \quad 0$$

$$0 \quad D(2) \quad 0 \quad 0 \quad D(2) \quad 0$$

$$0 \quad D(3) - 0.5 \quad D^{2}(5) \times (2) \quad 0$$

$$0 \quad D(3) - 0.5 \quad D^{2}(5) \times (6) \quad 0$$

$$D(4) - 0.5 \quad D^{2}(5) \times (6) \quad 0$$

$$D(7) - 0.5 \quad D^{2}(5) \times (9) \quad 0$$

$$D(7) - 0.5 \quad D^{2}(5) \times (9) \quad 0$$

$$D(3) - 0.5 \quad D^{2}(5) \times (2) \quad 0$$

$$D(3) - 0.5 \quad D^{2}(5) \times (2) \quad 0$$

$$D(7) - 0.5 \quad D^{2}(5) \times (2) \quad 0$$

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$$D(7) - 0.5 \quad D^{2}(5) \times (2) \quad 0$$

$$D(7) - 0.5 \quad D^{2}(5) \times (2) \quad 0$$

0

(7 + 32)

 $D(4) = 0.5 D^2(5) \times (6)$

- 367 -

By using the above equations (7-23) to (7-32) and the general iteration algorithm shown in equations (7-9) and (7-10), the digital computer program is shown in Appendix 2.1.

A.1.3. Digital computer computation for determination of coefficient \$\beta_{12}\$ (Optimal P of OAC scheme)

From Chapter 5, the derived three simultaneous equations (5-42), (5-43) and (5-47) are rewritten below:

$$K_3 + a_{11}B_{11} + a_{21}B_{12} - 0.25 b^2 B_{12}^2 = 0 (7-33)$$

$$a_{12}\beta_{11} + (a_{11} + a_{22})\beta_{12} + a_{21}\beta_{22} - 0.5 b^2 \beta_{12}\beta_{22} = 0$$
 (7-34)

$$d_{11}\beta_{12} + a_{22}\beta_{22} - 0.25 b^2 \beta_{22}^2 = 0 (7-35)$$

Let

$$x(1) = \beta_{11}$$
 $P = K_3$ $D(3) = a_{21}$ }
 $x(2) = \beta_{12}$ $D(1) = a_{11}$ $D(4) = a_{22}$ }
 $x(3) = \beta_{22}$ $D(2) = a_{12}$ $D(5) = b$ } (7-36)

and

F(1), F(F) and F(3) represent (7-33), (7-34) and (7-35) respectively.

Then:

$$F(1) = P + D(1) \times (1) + D(3) \times (2) - 0.25 D^{2}(5) \times^{2} (2)$$
 (7-37)

$$F(1) = D(2) \times (1) + (D(1) + D(4)) \times (2) + D(3) \times (3)$$

$$-0.5 D^{2}(5) \times (2) \times (3)$$
 (7-38)

$$F(3) = D(2) \times (2) + D(4) \times (3) - 0.25 D^{2}(5) \times^{2} (3)$$
 (7-39)

and
$$\frac{\partial F}{\partial X} =$$

$$\begin{bmatrix} D(1) & D(3) - 0.5 & D^{2}(5) & x & (2) & 0 \\ D(2) & D(1) + D(4) - 0.5 & D^{2}(5) & x & (3) & D(3) - 0.5 & D^{2}(5) & x & (2) \\ 0 & D(2) & D(4) - 0.5 & D^{2}(5) & x & (3) & (7-40) \end{bmatrix}$$

By using the above equations (7-37) to (7-40) and the general iteration algorithm, the digital computer program is shown in Appendix 2.2.

Al.4 Digital computer computation for determination of the coefficients \$321 and \$326. (Optimal P + I of OAC scheme)

From Chapter 5, the derived six simultaneous equations (5-77), (5-78), (5-82), (5-83), (5-84) and (5-38) are rewritten below:

$$2K_{3} = 2a_{11}\beta_{11} + a_{21}\beta_{12} + a_{21}\beta_{21} - 0.5 b^{2}\beta_{12}\beta_{21} + \beta_{16} = 0 \quad (7-41)$$

$$a_{12}\beta_{11} + (a_{11} + a_{22})\beta_{12} + a_{21}\beta_{22} - 0.5 \beta_{12}\beta_{22} = 0 \quad (7-42)$$

$$a_{11}\beta_{16} + a_{21}\beta_{26} - 0.5 b^{2}\beta_{12}\beta_{26} + \epsilon_{1} = 0 \quad (7-43)$$

$$a_{12}\beta_{11} + (a_{11} + a_{22})\beta_{21} + a_{21}\beta_{22} - 0.5 b^{2}\beta_{21}\beta_{22} + \beta_{26} = 0 \quad (7-44)$$

$$a_{12}\beta_{12} + a_{12}\beta_{21} + 2 a_{22}\beta_{22} - 0.5 b^{2}\beta_{22}^{2} = 0 \quad (7-45)$$

$$a_{12}\beta_{16} + a_{22}\beta_{26} - 0.5 b^{2}\beta_{22}\beta_{26} + \epsilon_{2} = 0 \quad (7-46)$$

Let
$$x(1) = B_{11}$$
 $D(1) = a_{11}$ $P = K_3$
 $x(2) = B_{12}$ $D(2) = a_{11}$ a_{11} a_{12} a_{13} a_{14} a_{15} a_{15} a_{16} $a_{$

and F(1), F(2),.....F(6) represent the six equations respectively, then equations (7-41) to (7-46) become:

$$F(1) = 2P + 2D(1) \times (1) + D(3) \times (2) + D(3) \times (4)$$

$$= 0.5 D^{2}(5) \times (2) \times (4) + \times (3)$$
(7.48)

$$F(2) = D(2) \times (1) + (D(1) + D(4)) \times (2) + D(3) \times (5)$$

$$= 0.5 D^{2}(5) \times (2) \times (5)$$
(7-49)

$$F(3) = D(1) \times (3) + D(3) \times (6) - 0.5 D^{2}(5) \times (2) \times (6) + G$$
 (7-50)

$$F(4) = D(2) \times (1) + (D(1) + D(4)) \times (4) + D(3) \times (5)$$

$$= 0.5 D^{2}(5) \times (4) \times (5) + \times (6)$$
(7-51)

$$F(5) = D(2) \times (2) + D(2) \times (4) + 2D(4) \times (5)$$

$$= 0.5 D^{2}(5) \times^{2}(5)$$
(7-52)

$$F(6) = D(2) \times (3) + D(4) \times (6) - 0.5 D^{2}(5) \times (6) + G$$
 (7-53)

and:

$$\frac{\partial F}{\partial x} =$$

By using the above equations (7-48) to (7-54) and the general iteration algorithm, the digital computer program is shown in Appendix 2.3.

A1.5. Digital computer computation for determination of the coefficients B 21, B 26 and B 27 (Optimal P + I + D of OAC scheme)

From Chapter 5, the derived ten simultaneous equations (5-124), (5-125), (5-126), (5-129), (5-130), (5-131), (5-132), (5-133), (5-136) and (5-137) are rewritten below:

$$2K_{3} + 2a_{11}^{6}_{11} + a_{21}^{6}_{12} + \beta_{16} + a_{11}^{2}_{17} + a_{21}^{6}_{21} + a_{11}^{2}_{21} + a_{11}^{2}_{21} + a_{21}^{6}_{27} = 0$$
 (7-55)

$$a_{12}B_{11} + (a_{11} + a_{22})B_{12} + a_{11}a_{12}B_{17} + a_{21}B_{22}$$

$$+ a_{12}a_{21}B_{27} - 0.5 b^2 B_{12}B_{22} - 0.5 b^2 a_{12}B_{12}B_{27} = 0$$
 (7-56)

$$-2K_3 + a_{11}B_{13} - B_{16} + a_{21}B_{23} - 0.5 b^2 B_{12}B_{23} = 0 (7-57)$$

$$a_{11}\beta_{16} + a_{21}\beta_{26} - 0.5 b^2 \beta_{12}\beta_{26} + \epsilon_1$$
 = 0 (7-58)

$$\beta_{13} - a_{11}\beta_{17} - a_{21}\beta_{27} + 0.5 b^2 \beta_{12}\beta_{27} = 0$$
 (7-59)

$$a_{12}\beta_{11} + a_{11}a_{12}\beta_{17} + (a_{11} + a_{22})\beta_{21} + a_{21}\beta_{22} + \beta_{26}$$

$$+ a_{11}a_{22}\beta_{27} - 0.5 b^{2}\beta_{21}\beta_{22} - 0.5 b^{2}a_{11}a_{22}\beta_{27} = 0 (7-60)$$

$$a_{12}\beta_{12} + a_{12}^{2}\beta_{17} + a_{12}\beta_{21} + 2a_{22}\beta_{22} + a_{12}a_{22}\beta_{27}$$

$$-0.5 b^{2}\beta_{22}^{2} - 0.5 b^{2}a_{12}\beta_{22}^{2}$$

$$= 0 (7-61)$$

$$a_{12}^{n}_{13} + a_{22}^{n}_{23} - n_{26} - 0.5 b^{2}_{3}_{22}^{n}_{23} = 0 \quad (7-62)$$

$$a_{12}\beta_{16} + a_{22}\beta_{26} - 0.5 b^2 \beta_{22}\beta_{26} + \epsilon_2 = 0$$
 (7-63)

$$-a_{12}\beta_{17} - a_{22}\beta_{27} + \beta_{23} + 0.5b^2\beta_{22}\beta_{27} = 0 (7-64)$$

Let:

$$x(1) = \beta_{11}$$
 $x(6) = \beta_{21}$ $D(1) = a_{11}$ $P = K_3$
 $x(2) = \beta_{12}$ $x(7) = \beta_{22}$ $D(2) = a_{12}$ $\epsilon_1 = \epsilon_2 = G$
 $x(3) = \beta_{13}$ $x(8) = \beta_{23}$ $D(3) = a_{21}$
 $x(4) = \beta_{16}$ $x(9) = \beta_{26}$ $D(4) = a_{22}$
 $x(5) = \beta_{17}$ $x(10) = \beta_{27}$ $D(5) = b$ $(7-65)$

and let $F_1(+)$, $F_2(t)$, F(10) represent the above ten equations respectively.

Then equations (7-55) to (7-64) become:

Then equations (7-55) to (7-64) become:

$$F(1) = 2P + 2D(1) \times (1) + D(3) \times (2) + x(4) + D^{2}(1) \times (5) + D(3) \times (6) + D(1)D(3) \times (10) - 0.5 D^{2}(5) \times (2) \times (6) - 0.5 D^{2}(5)D(1) \times (2) \times (10)$$

$$F(2) = D(2) \times (1) + (D(1) + D(4)) \times (2) + D(1)D(2) \times (5) + D(3) \times (7) + D(2)D(3) \times (10) - 0.5 D^{2}(5) \times (2) \times (7) - 0.5 D^{2}(5)D(2) \times (2) \times (10)$$

$$F(3) = -2P + D(1) \times (3) - x(4) + D(3) \times (8) - 0.5 D^{2}(5) \times (2) \times (8) - (7-68)$$

$$F(4) = D(1) \times (4) + D(3) \times (9) - 0.5 D^{2}(5) \times (2) \times (9) + G$$

$$F(5) = x(3) - D(1) \times (5) - D(3) \times (10) + 0.5 D^{2}(5) \times (2) \times (10)$$

$$F(6) = D(2) \times (1) + D(1)D(2) \times (5) + (D(1) + D(4)) \times (6) + D(3) \times (7) + x(9) + D(1)D(4) \times (10) - 0.5 D^{2}(5) \times (2) \times (10)$$

$$F(7) = D(2) \times (2) + D^{2}(2) \times (5) + D(2) \times (6) + 2D(4) \times (7)$$

$$+ D(2)D(4) \times (10) - 0.5 D^{2}(5) \times ^{2}(7) -$$

 $-0.5 D^{2}(5)D(2) \times (7) \times (10)$

$$F(8) = D(2) \times (3) + D(4) \times (8) - x(9) - 0.5 D^{2}(5) \times (7) \times (8)$$
 (7-73)

$$F(9) = D(2) \times (4) + D(4) \times (9) - 0.5 D^{2}(5) \times (7) \times (9) + G$$
 (7-74)

$$F(10) = -D(2) \times (5) - D(4) \times (10) + x(8) + 0.5 D^{2}(5) \times (7) \times (10)$$
 (7-75)

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or.	0(3)-0.502(5)x(2)	0	0	0	0	D(1)+D(4)-0.5D*(5)x(7)	D(2)	•	0	0		25: 3x.e	D(1)0(3)-0.50 (5)0(1)x(2)	D(1) 0(1) -0.5 0 (1) 0(1) x (1)	0	•	-0(1)+0.50"(5) x(2)	D(1)0(4)-0.50(5)0(1)x(7)	0(1)0(4)-0.502(3)0(1)x(1)		۰	-D(4)+0.503(5)x(7)	
3F:	(1)20	(1)0(1)	o	0	(1)0-	06)0(3)	0,(1)	0	0	0 (1)		oxe.	0		0	D(3)-0.50 (3) x (3)	0	-	0	:	D(4)-0.5 D(5) x(1)	0	
3F: 3F:	•	•	1- (00	0 0(1)	•	0	0	0 ()0	0 (2)	0		3.F.;	0	0	D(1) -0.503(5) x (2)	0	0	0	0	D(4)-0.50 (5) x (7)	0		
3.F.	2 D(+) D(3)-0.502(5)x(6)-0.502(5)O(1)x(10)	D(1)+D(4)-0.502(5)x(7)-0.502(5)D(2)x(10)	- 0.50°(5)x(8)	- 0.5 02(5) x (9)	+ 0.5 0*(5) x (10)	0	0 (1)	0	•	0	84)	DF:	0	D(3)-0.502(5)x(2)	O (1)-0-	•	•	D(3) _ 0.5 D(5)x(6)- 0.5 D(5) D(1)x(10)	20(4)-0.50'(5)x(7)-0.50'(5)0(2)x(10)	-0.50 (8) 0(4)-0.5	-0.50'(S)x(9)	+0.5 D3(5)x(10)	
or.	20(1)	0(1)	0	0	0	(1)0	0	٥	0	0								0(3)-0	20(4)-				

By using above equations (7.65) ~ (7.75) and general iteration algorithm; the digital computer programming is shown on Appendix 2-4

-374-

APPENDIX 2

Digital Computer Programming

A 2.1 Computer Programming -1 (based on A1-2)

```
MASTER ADAPT=1
CERT DETERMINATION OF OPTIMAL CONTROL LAW COEFFICIENTS X(1),X(6),X(7)
C
     x(8),x(0) BY NEWTON-RAPHSON METHOD
DIMENSION D(7), Y(9), X(9), F(9), A(9,9), B(9,9), R(9), C(81), W(81), P(2)
     PEAD(1,2)(D(I),I=1,7)
2 FORMAT(7F10.5)
     WRITE(2,4)
TENT 4 FORMAT (/3X, 'P(1), P(2) ARE WEIGHTING FACTORS X1(9), X2(9),... ARE!
         /2X, IN SEQUENCE, THE FIRST NUMBERS ARE THE INITIAL GUESS! //)
   WRITE(2,5)
   5 FORMAT(/9X,'X(1)',8x,'X(2)',8X,'X(3)',8x,'X(4)',8X,'X(5)',8X,
1'X(6)',8x,'X(7)',8X,'X(8)',8X,'X(9)',/)
6 p(1)pH
HH=2.0
8 P(2)=HH
      WRITE(2,10)P(1),P(2)
無意 10 FORMAT(/8X,'P(1)=',F5.2,5X,'P(2)=',F5.2/)
      DO 12 I=1.9
12 v(I)=0.0
14 b0 16 I=1,9
16 X(I)=Y(I)
                  Line in the fathering on the Trains of the
   11=1
18 WRITE(2,20)(X(I),I=1,9)
20 FORMAT(/3X,9(2X,F10.5)/)
DEFINE VECTOR F(9) AND MATRIX A(9,9)
      F(1) = P(1) + D(1) + X(1) + D(3) + X(2) = 0.250 + D(5) + D(5) + X(2) + X(2)
    F(2)=D(2)*X(1)+(D(1.)+D(4))*X(2)+D(3)*X(6)
1-0.500+D(5)+D(5)+X(2)+X(6)
F(3)=-2.*P(1)+D(1)+x(3)+D(3)*X(7)*0.500*D(5)*D(5)*X(2)*X(7)
      F(4) = D(6) + X(1) + D(1) + X(4) + D(3) + X(8) - 0,500 + D(5) + D(5) + X(2) + X(8)
F(6)=P(2)+D(2)*X(2)+D(4)*X(6)=0.250*D(5)*D(5)*X(6)*X(6)
r(7) =D(2) +X(3) +D(4) +X(7) =0.500+D(5) +D(5) +X(6) +X(7)
F(8)=D(6)+X(2)+D(2)+X(4)+D(4)+X(8)=0.500+D(5)+D(5)+X(6)+X(8)
声記です。F(9)=D(2)+X(5)+D(7)+X(6)+D(4)+X(9)=0.500+D(5)+D(5)+X(6)+X(9)
A(1,1)=D(1)
A(1,2)=D(3)=0.500+D(5)+D(5)+X(2)
A(1,3)=0.0
A(1,4)=0.0
      A(1,5)=0.0
A(1,6)=0.0
      A(1,7)=0.0
A(1,8)=0.0
A(1,9)=0.0
A(2,1)=D(2)
      A(2,2)=(D(1)+D(4))=0.500+D(5)+D(5)+X(6)
```

```
A(2,3)=0.0
     A(2,4)=0.0
     A(2,5)=0.0
     A(2,6)=D(3)=0.500+D(5)+D(5)+X(2)
     A(2,7)=0.0
     A(2,8)=0.0
     0.0=(P,S)A
     A(3,1)=0.0
     A(3,2)==0.500+D(5)+D(5)+X(7)
     A(3,3)=D(1)
A(3,4)=0.0
     A(3,5)=0.0
\Lambda(3,6)=0.0
     A(3,7)=D(3)-0.500+D(5)+D(5)+X(2)
A(3,8)=0.0
     \Lambda(3,9)=0.0
     A(4,1)=D(6)
     A(4,2) = -0.500 * D(5) * D(5) * X(8)
 A(4,3)=0
     A(4,4)=D(1)
A(4,5)=0.0
     A(4,6)=0.0
A(4,7)=0.0
     A(4,8)=D(3)=0.5C0+D(5)+D(5)+X(2)
A(4,9)=0.0
     A(5,1)=0.0
  A(5,2)=D(7)=0.500+D(5)+D(5)+X(9)
     A(5,3)=0.0
A(5,4)-0.0
     \Lambda(5,5) = O(1)
 A(5,6)=0.0
     A(5,7)=0.0
A(5,8)=0.0
     A(5,9)=D(3)=0,500+D(5)+D(5)+X(2)
A(6,1)=0.0
     V(2) = V(3)
A(6,3)=0.0
      A(6,4)=0.0
     A(6,5)=0.0
     A(6,6)=D(4)=0.500+D(5)+D(5)+X(6)
A(6,7)=0.0
      A(6,8)=0.0
A(6,9)=0.0
      A(7,1)=0.0
A(7,2)=0.0
      A(7,3)=D(2)
A(7,4)=0.0
                   \Lambda(7.5)=0.0
 A(7,6)=-0.500+D(5)+D(5)+X(7)
     A(7,7)=D(4)-0,500+D(5)+D(5)+X(6)
A(7,8)=0.0
A(8,1)=0.0
     A(8,1)=0.0
A(8,2)=D(6)
A(8,3)=0.0
A(8,4)=D(2)
A(8,5)=0.0
FOOTB(5)+D(5)+Y(8)
A(8,6)=-0.500+D(5)+D(5)+X(8)
 A(8,7)=0.0
   A(8,8)=D(4)=0.500+D(5)+D(5)+X(6)
```

```
A(8,9)=0.0
A(9,1)=0.0
 A(9,2)=0.0
A(9,3)=0.0
A(9,4)=0.0
A(9,5)=D(2)
A(9,6)=D(7)=0.500+D(5)+D(5)+X(9)
A(9,7)=0.0
A(9,7)=0.0
A(9,8)=0.0
A(9,9)=D(4)=0.500+D(5)+D(5)+X(6)
no 22 J=1.9
    DO 22 I=1,9
C(L)=A(I,J)
L=L+1
DO 22 I=1.9
22 L=L+1
CALL EDNOCATION D. A.C.
    N=9
    CALL FPMGEIN(N, E, C(1), W(1), DET, IRANK, NRR)
DO 24 Jul.9
D0 24 I=1,9
p(I,J)=C(L)
  24 L=L+1
    00 28 1=1.9
R(1)=0.0
    DO 26 J±1.9
26 R(I)=R(I)+B(I,J)+F(J)
X(I)=X(I)=R(I)
-28 CONTINUE
II=II+1
 #### FIF(II-10) 30,30,48
30 IF(ABS(R(1))=0.0100) 32,18,18
32 IF(ABS(R(2))-0.0100) 34,18,18
34 IF(ABS(R(3))=0.0100) 36,18,18
36 JF(ABS(R(4))=0.0100) 38,18,18
38 IF(ABS(R(5))=0.0100) 40,18,18
40 IF(ABS(R(6))-0.0100) 42,18,18
42 IF(ABS(R(7))-0.0100) 44,18,18
44 IF(ABS(R(8))=0.0100) 46.18.18
46 IF(ABS(R(9))=0.0100) 48.18.18
48 DO 50 I=1.9
50 Y(I)=Y(I)+1.
TF(Y(1)=1.5) 52,52,56
52 WRITE(2,54)
54 FORMAT(/.3X, 'USE NEW GUESS'./)
    GO TO 14
           N 59.50.40
56 HH=HH+2.0
    TF(HH-11.0) 58,58,60
58 GO TO 8
60 H=H+2.0
1F(H-11.0) 62,62,64
62 GO TO 6
64 STOP
END
```

A 2.2 Computer Programming -2 (based on A1-3)

```
MASTER ADAPT-2
 C THE DETERMINATION OF OPTIMAL CONTROL LAW COEFFICIENTS X(2) BY NEWTON-
                PADIISON METHOD
  DIMENSION D(5),Y(3),X(3),F(3),A(3,3),B(3,3),R(3),C(9),W(9)
                READ(1,2)(D(1),1=1,5)
2 FORMAT (5 F10.5)
4 FORMAT (/3X, 1 P ARE WEIGHTING FACTOR X1(3), X2(3), ... ARE IN!/
                                 /2X, 'SEQUENCE, THE FIRST NUMBERS ARE THE INITIAL GUESS', /)
   5 FORMAT(/12X,'X(1)',11X,'X(2)',11X,'X(3)',/)
p=50.0
6 WRITE(2,10) P
10 FORMAT (/10X, 'P=', F5.2/)
                DO 12 T=1.3
12 Y(I)=0.0
14 DO 16 I=1.3
16 y(1)=y(1)
18 URITE(2,20)(X(1),1=1,3)
     20 FORMAT (/3X, 3F15, 5/)
C DEFINE VECTOR F(3) AND MATRIX A(3.3)
               F(1)=P+n(1)*X(1)+D(3)*X(2)=0.250*D(5)*D(5)*X(2)*X(2)
F(2)=D(3)+X(1)+(D(1)+D(4))+X(2)+D(3)+X(3)
1 -0.500*D(5)*D(5)*X(2)*X(3)
F(3)=D(2)*X(2)+D(4)*X(3)-0.250*D(5)*D(5)*X(3)*X(3)
                A(1,1)=D(1)
 A(1,2)=D(3)-0.500+D(5)+D(5)+X(2)
                A(1,3)=0.0
  A(2,1)=0.0
(2)
  A(2,2)=D(1)+D(4)-0.500*D(5)*D(5)*X(3)
A(2,3)=D(3)-0.500*D(5)*D(5)*X(2)
                A(3,1)=0.0
 V(3,2)=D(2)
                                                                                                        A(3,3)=D(4)-0.500+D(5)+D(5)+X(3)
DO 22 J=1.3
          DO 22 1=1.3
                C(L)=A(I,J)
22 L=L+1
              N=3
 E=0.0001
                                                               graph personal control of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the section of the sectio
                CALL FPMGEIN(N, E, C(1), W(1), DET, IRANK, NRR)
```

```
L=1 00 24 J=1,3
   00 24 I=1.3
   B(1, J)=C(L)
24 L=L+1
00 28 I=1,3
   R(I)=0.0
DO 26 J=1.3
 R(I)=0.0
26 R(I)=R(I)+B(I,J)+F(J)
   X(1)=X(1)-R(1)
 28 CONTINUE
11=11+1

IF(11-15) 30,30,36

30 IF(ABS(R(1))=0,0100) 32,18,18
32 1F(ARS(P(2))-0,6100) 34,18,18
  34 (F(ARS(P(3))=0.0100) 36,18,18
36 po 38 I=1.3
  38 Y(1)=Y(1)+1.

JF(Y(1)-1.5) 40,40,44
  40 WRITE(2,42)
  42 FORMAT (/3X, 'USE NEW GUESS',/)
  ... GU TO 14
        44 P=P+50.0
1F(P-1005.0) 46,46,48
46 GO TO 6
48 STOP
END
```

A 2.3 Computer Programming -3 (based on A1-4)

```
MASTER ADAPT=3
      DETERMINATION OF OPTIMAL CONTROL LAW COEFFICIENTS X(4) AND X(6)
C
C
      BY NEWTON-RAPHSON METHOD
      DIMENSION D(5), Y(6), X(6), F(6), A(6,6), B(6,6), R(6), C(36), W(36)
      READ(1,2)(D(1),1=1,5)
    2 FORMAT (5F10.5)
      WRITE(2,4)
    4 FORMAT(/3X, 'P ARE WEIGHTING FACTOR X1(6), X2(6), ... ARE IN'/
            /2X, 'SEQUENCE, THE FIRST NUMBERS ARE THE INITIAL GUESS', /)
     WRITE(2,5)
    5 FORMAT (/12x, 'X(1)', 11X, 'X(2)', 11x, 'X(3)', 11x, 'X(4)', 11X, 'X(5)'
     1,11X,'X(6)',/)
      p=100.0
    6 WRITE(2,8) P
    8 FORMAT (/10x, 'P=', F5.2/)
      G=0.0
    9 WRITE(2,10) G
   10 FORMAT(/10X, 'G=', F5.2/)
      DO 12 1=1,6
   12 y(I)=0.0
   14 no 16 I=1.6
   16 \chi(1) = \gamma(1)
      11=1
   18 URITE(2,20)(X(1),1=1,6)
   20 FORMAT (/3X,6F15.5/)
      DEFINE VECTOR F(6) AND MATRIX A(6,6)
C
      F(1)=2,*P +2,*D(1)*X(1)+D(3)*X(2)+D(3)*X(4)
     1=0.500*D(5)*D(5)*X(2)*X(4)+x(3)
      g(2)=D(2)*X(1)+(D(1)+D(4))*X(2)+D(3)*X(5)
     1=0.500*D(5)*D(5)*X(2)*X(5)
    F(3)=D(1)*X(3)+D(3)*X(6)-0.500*D(5)*D(5)*X(2)*X(6)+G
      g(4)=D(2)*X(1)*(D(1)+D(4))*X(4)+D(3)*X(5)
     1-0.500*D(5)*D(5)*X(4)*X(5)+X(6)
     #(5)=D(2)*X(2)+D(2)*X(4)+2.*D(4)*X(5)=0.500*D(5)*D(5)*X(5)*X(5)
     F(6)=D(2)*X(3)*D(4)*X(6)=O.500*D(5)*D(5)*X(5)*X(6)*G
      A(1,1)=2,*D(1)
      A(1,2)=D(3)-0.500*D(5)*D(5)*X(4)
      A(1,3)=1.
      A(1,4)=D(3)=0.500*D(5)*D(5)*X(2)
      A(1,5)=0.0
      A(1,6)=0.0
     A(2,1)=D(2)
     A(2,2)=D(1)+D(4)=0.500+D(5)+D(5)+X(5)
    A(2,3)=0.0
     A(2,4)=0.0
     A(2,5)=D(3)-0.500+D(5)+D(5)+\chi(2)
     A(2,6)=0.0
     A(3,1)=0.0
     A(3,2)=-0.500+D(5)+D(5)+\chi(6)
     A(3,3)=D(1)
     \Lambda(3,4)=0.0
   A(3,5)=0.0
     A(3,6)=D(3)=0,500*D(5)*D(5)*X(2)
```

```
A(4,1)=D(2)
   A(4,2)=0.0
   A(4,3)=0.0
   A(4,4)=D(1)+D(4)=0.500+D(5)+D(5)+X(5)
   A(4,5)=D(3)=0.500*D(5)*D(5)*X(4)
   A(4,6)=1.
   A(5,1)=0.0
   A(5,2)=D(2)
   A(5,3)=0.0
   A(5,4)=D(2)
   A(5,5)=2, +D(4) mD(5) +D(5) +X(5)
   A(5,6)=0.0
  A(6,1)=0.0
   A(6,2)=0.0
   A(6,3)=D(2)
  A(6,4)=0.0
  A(6,5)=-0.500+D(5)+D(5)+X(6)
  A(6,6)=D(4)=0.500*D(5)*D(5)*X(5)
  L=1
  DO 22 J=1.6
  00 22 1=1.6
  C(L)=A(I,J)
22 L=L+1
  N=6
  E=0.0001
  CALL FPMGEIN(N, E, C(1), W(1), DET, IRANK, NRR)
  L=1
  DO 24 J=1,6
  00 24 1=1.6
  B(I, J)=C(L)
24 L=L+1
... po 28 I=1,6 . ....
  R(I)=0.0
DO 26 J=1,6
26 R(I)=R(I)+B(I,J)+F(J)
  X(I)=X(I)=R(I)
28 CONTINUE
  11=11+1
  1F(11-30) 30,30,42
30 IF(ABS(R(1))-0,0100) 32,18,18
32 IF(ABS(R(2))-0,0100) 34,18,18
34 1F(ABS(R(3))=0,0100) 36,18,18
36 FF(ABS(R(4))-0,0100) 38,18,18
38 IF(ABS(R(5))=0,0100) 40,18,18
40 IF(ABS(R(6))+0.0100) 42,18,18
42 DO 44 I=1,6
44 Y(I)=Y(I)+1.
  IF(Y(1)-1.5) 46,46,49
46 WRITE(2,48)
48 FORMAT (/3X, 'USE NEW GUESS',/)
  GO TO 14
49 G=G+0.2
  IF(G-1.5) 50,50,51
50 go to 9
50 GO TO 9
51 P=P+100.0
  IF(P-550.0) 52,52,54
52 GO TO 6
54 STOP
  END
```

A 2.4 Computer Programming -4 (based on A1-5)

```
رائي والمحادث وموده مورويون مودويها الانتاء المعالي المناسب المال والمعالج المتعالج
MASTER ADAPT-4
- C ---- DETERMINATION OF OPTIMAL CONTROL LAW COEFFICIENTS X(6),X(9)AND
     x(10) BY NEWTON-RAPHSON METHOD
 - DIMENSION D(5), Y(10), X(10), F(10), A(10,10), B(10,10), R(10), C(100),
    CW(100)
= PEAD(1,2)(D(I),I=1,5)
2 FORMAT (5F10.5)
BOTH NRITE(2,4) ---
 4 FORMAT(/3X, P ARE WEIGHTING FACTOR X1(10).X2(10),..., ARE IN'/
C - /2X, 'SEQUENCE, THE FIRST NUMBERS ARE THE INITIAL GUESS',/)
WRITE(2,5)
5 FORMAT (/8X, 'X(1)',7X, 'X(2)',7X, 'X(3)',7X, 'X(4)',7X, 'X(5)',7X,
----1'X(6)',7X,'X(7)',7X,'X(8)',7X,'X(9)',7X,'X(10)',/)
6 WRITE(2,10) P
10 FORMAT (/10X, 'P"', F5.2/)
6=0.0
100 FORMAT(/10X, 'G=', F5.2/)
= 12 y(1)=0.0 -
-----16 x(1)=Y(1)
                     gangergan (III) ika manggalas kemananan ngawas ngala gangan nga kalangan ngalangan ngangan ngangan ngangan nga
- -- 18 URITE(2,20)(X(I),I=1,10)
20 FORMAT (/2X,10(1X,F10.4)/)
C -- DEFINE VECTOR F(10) AND MATRIX A(10,10)
 = ---- 2---- 2---- = -0.500*D(5)*D(5)*D(1)*X(2)*X(10)
 F(2)=D(2)*X(1)+(D(1)+D(4))*X(2)+D(1)*D(2)*X(5)+D(3)*X(7)
+D(2)*D(3)*X(10)*0.500+D(5)*D(5)*X(2)*X(7)
2 -0,500*D(5)*D(5)*D(2)*X(2)*X(10)
- F(3)=-2.*P+D(1)*X(3)*X(4)+D(3)*X(8)*O.500*D(5)*D(5)*X(2)*X(8)
F(4)=D(1)+X(4)+D(3)+X(9)-0.500+D(5)+D(5)+X(2)+X(9)+G
r(5) xx(3) -D(1) +x(5) -D(3) +x(10) +0.500 +D(5) +D(5) +x(2) +x(10)
--- #(6)=D(2)*X(1)+D(1)*D(2)*X(5)+(D(1)+D(4))*X(6)+D(3)*X(7)+X(9)
- - 2 - - 0.500*D(5)*D(5)*D(1)*X(7)*X(10)
F(7)=D(2)*X(2)+D(2)*D(2)*X(5)+D(7)*X(6)+2.*D(4)*X(7)

1 +D(2)*D(4)*X(10)=0.500*D(5)*D(5)*X(7)*X(7)

-0.500*D(5)*D(5)*D(2)*X(7)*X(10)
 F(8)=D(2)+X(3)+D(4)+X(8)-X(0)-0.500+D(5)+D(5)+X(7)+X(8)
F(9)=D(2)+X(4)+D(4)+X(9)=0.500+D(5)+D(5)+X(7)+X(9)+G
F(10)=-D(2)+X(5)-D(4)+X(10)+X(8)+0.500+D(5)+D(5)+X(7)+X(10)
-A(1,1)=2.*D(1)
 A(1,2)=D(3)=0.500+D(5)+D(5)+X(6)=0.500+D(5)+D(5)+D(1)+X(10)
 A(1.3)=0.0
                 ್ ನ್ ಕುರ್ನ್ನು ಎಂದು ಸಂಚಿತ
 A(1,4)=1.
```

```
A(1,6)=D(3)=0.500+D(5)+D(5)+X(2)
  ---A(1,7)=0.0
    A(1,8)=0.0
  _____A(1,9)=0.0
  A(1,10)=D(1)+D(3)=0.500+D(5)+D(5)+D(1)+X(2)
 A(2,1)=D(2)
    A(2,2)=D(1)+D(4)=0.500+D(5)+D(5)+X(7)=0.500+D(5)+D(5)+D(2)+X(10)
 A(2,4)=0.0
 A(2,5)=D(1)+D(2)
0.0=(8,5)A
A(2,7)=D(3)=0,500+D(5)+D(5)+X(2)
    A(2,8)=0.0
  - V(5'8)=0:0
    A(2,10)=D(2)+D(3)-0.500+D(5)+D(5)+D(2)+X(2)
A(3,1)=0.0
A(3,2)==0.500+D(5)+D(5)+X(8)
A(3,4)==1.
A(3,5)=0.0
A(3,6)=0.0
A(3,6)=0.0

A(3,7)=0.0

A(3,8)=D(3)=0.500*D(5)*D(5)*X(2)
A(3,9)=0.0
A(3,10)=0.0
A(4,1)=0,0
A(4,2)==0.500+D(5)+D(5)+X(9)
A(4,4)=D(1)
A(4,5) = 0.0
A(4,6) = 0.0
A(4,7)=0.0
A(4,8)=0.0
A(4,9)=D(3)=0.500+D(5)+D(5)+\chi(2)
A(4,10)=0.0
A(5,1)=0.0
A(5,2)=0.500+D(5)+D(5)+X(10)
   --A(5,3)=1.
A(5,4)=0.
A(5,4)=0.
A(5,6)=0.0
A(5,7)=0.0 ---
A(5,9)=0.0
A(5,10)==D(3)+0.500+D(5)+D(5)+X(2)
A(6,2)=0.0
A(6,3)=0.0
A(6,4)=0.0
A(6,5)=D(1)+D(2)
 A(6,6)=D(1)+D(4)=0.500+D(5)+D(5)+X(7)
A(6,7)=D(3)-0.500+D(5)+D(5)+X(6)-0.500+D(5)+D(5)+D(1)+X(10)
A(6,8)=0.0
Λ(6.9)=1.
A(6,10) =D(1) +D(4) =0,500 +D(5) +D(5) +D(1) +X(7)
 A(7,1)=0.0
A(7,2)=D(2)
```

```
A(7,3)=0.0
A(7,4)=0.0
Λ(7,5) =D(2) +D(2)
Λ(7,6) =D(2)
A(7,7)=2.*D(4)=0.500+D(5)+D(5)+X(7)=0.500+D(5)+D(5)+D(2)+X(10)
A(7,8)=0.0
A(7,9)=0.0
A(7,9)=0.0
 A(7,10)=D(2)+D(4)=0.500+D(5)+D(5)+D(2)+X(7)
A(8,2)=0.0
A(8,3)=D(2)
A(8,4)=0.0
A(8,5)=0.0
A(8,6)=0.0
A(8,7) = -0.500 + D(5) + D(5) + X(8)
A(8,8) = D(4) - 0.500 + D(5) + D(5) + X(7)
A(8,9)=-1.
A(8,10)=0.0
A(9,1)=0.0
A(9,2)=0.0
A(9,3)=0.0
A(9,4)=D(2)
     A(9,5)=0.0
     A(9,6)=0.0
A(9,7)==0.500+D(5)+D(5)+X(9)
A(9,8)=0.0
A(9,9)=D(4)=0.500*D(5)*D(5)*X(7)
A(9,10)=0.0
A(10,1)=0.0
A(10,2)=0.0
A(10,3)=0.0
A(10,4)=0.0
A(10,5)=D(2)
A(10,6)=0.0
A(10,7)=0.500+D(5)+D(5)+X(10)
A(10,8)=1.
A(10,8)=1.
A(10,9)=0.
A(10,10)=-D(4)+0.500+D(5)+D(5)+X(7)
no 22 J=1,10 -
C(L)=A(1,J)
 N=10
E=0.0001
CALL FPMGEIN(N,E,C(1),W(1),DET,IRANK,NRR)
00 24 J=1,10
DO 24 JEI/10
B(I,J)=C(L)
p0 28 I=1,10
 TO 26 J=1,10
     X(I)=K(I)+B(I,J)+F(J)
X(I)=X(I)-R(I)
CONTINUE
- - 26 q(I)=R(I)+B(I,J)+F(J)
28 CONTINUE
```

```
F(II-10) 30,30,50
    30 [F(ABS(R(1))-0.0100) 32,18,18
  -- 32 IF(ABS(R(2))-0.0100) 34,18,18
    34 IF(ABS(R(3))-0.0100) 36,18,18
    36 1F(ABS(R(4))-0.0100) 38,18,18
    38 [F(ABS(R(5))-0.0100) 40,18,18
 40 IF(ABS(R(6))-0.0100) 42,18,18
   42 1F(ABS(R(7))-0.0100) 44,18,18
44 IF(ABS(R(8))-0.0100) 46,18,18
   46 IF(ABS(R(9))-0.0100) 48,18,18
----- 48 JF(ABS(R(10))-0.0100) 50,18,18
50 no 52 I=1,10
52 v(I)=Y(I)+1.0
IF(Y(1)-1.2) 54.54.57
 ---54 URITE(2,56)
  - 56 FORMAT(/3X, 'USE NEW GUESS',/)
60 TO 14
 57 G=G+0.02
 - --- IF(G-0.11) 58,58,59
58 GO TO 11
1F(p-22.0) 60,60,62
59 P=P+5.0
60 GO TO 6
```

- A 2.5 Computer Programming -5 Calculation of velocity constant from Arrhenius Equation. T vs K Master Adapt-5 C Calculation of velocity constant from Arrhenius Equation Write (2.5) Format(5X, 'T', 12X, 'K',/) T=0.010 Y=6.30*(10,0**15.0)*EXP(-24000.0/(1.987*(273.0+T)))Write(2.15) T.Y 15 Format(3X, F5, 1, 5X, F6.4, /)T=T+1.0IF(T-100.0) 20.20.25 GO TO 10 20 25 STOP END A 2.6 Computer Programming -6 Calculation of velocity constant from Arrhenius equation. T vs $\begin{bmatrix} T \\ T \end{bmatrix}$ and $\begin{bmatrix} K \\ Km \end{bmatrix}$ Master Adapt-6 Calculation of velocity constant from Arrhenius Equation C Write(2.5) 5 Format(5X, 'T', 10X, 'T/TMAX', 10X, 'K/KMAX', /) T=0.010 X=T/40.0Y=EXP((-24000.0/C1.987*(273.0+T)))+(24000.0/(1.987*3.3.0)))Write(2.15) T.X.Y Format(/3X,F5.1,9X,F5.3,10X,F6.4,/) 15 T=T+1.0 IF(T-40.0) 20.20.25 20 GO TO 10 STOP 25 END
- A 2.7 Tables of computed α ; and β ; values (Tables A 2.1 A 2.4)

TABLE A.2.1. & ij values of OMR scheme computed from A.2.1.

	⁴ 11	~ 22	⁴ 23	d 24
$K_1 = 4$ $K_2 = 4$	28.1372	7.7681		
$K_1 = 8$ $K_2 = 8$	51.2233	14.4027	-28.4028	3.6851
$K_1 = 15$ $K_2 = 15$	85.4628	24.5025		

•	12
K ₃ = 100	99.50
K ₃ = 200	156.20
K ₃ = 500	273.67
K _z = 1000	410.00

Table A.2.3. β ij values of DAC scheme for optimal P+I control computed from A.2.3.

K3	=	100	ß ₂₁	ß 26
ę	=	0	99.502	0
٤	=	1	101.470	1.667
£	=	2	103.394	3.312
Ę	=	3	105.287	4.937
e	=	4	107.125	6.542
к3	=	200		
e	=	0	156.197	0
E	=	1	157.238	1.215
6	=	2	158.272	2.426
6	=	3	159.30	3.633
E	=	4	160.322	4.836
6	=	8	164.509	9.709
•	=	15	170.909	18.153
к3	=	100	ě	
E	=	0	99.502	0
E	=	0.2	99.899	0.335
ŧ	=	0.4	100.294	0.670
6	=	0.6	100.690	1.002
6	=	0.8	101.079	1.336
ŧ	=	1.0	101.470	1.667

Table A.2.3. (continued)

К3	=	200	ß ₂₁	ß 26
ŧ	=	0	156.197	0
E	=	0.2	156.406	0.243
E	=	0.4	156.614	0.487
•	=	0.6	156.822	0.730
E	=	0.8	157.030	0.973
e	=	1.0	157.238	1.215

Table A.2.4. β_{ij} values of OAC scheme for optimal P + I + D control computed from A.2.4.

K3	=	1.0	ß ₂₁	B 26	ß ₂₇
6	=	0.0	5.4653	0	54.4914
ŧ	=	0.5	28.2819	2.6588	262.3466
6	=	1.0	51.0984	5.3176	470.2018
E,	=	1.5	73.9150	7.9766	678.0570
E	=	2.0	96.7316	10.6352	885.9122
к3	=	3.0			
E	=	0.0	16.3959	0	163.4743
E	=	0.5	39.2124	2.6588	371.3295
E	=	1.0	. 62.0290	5.3176	579.1847
ŧ	=	1.5	84.8456	7.9766	787.0399
E	=	2.0	107.6622	10.6352	994.8951
К ₃	=	1.0			
٤	=	0.1	10.0286	0.5318	96.0625
E	=	0.2	14.5919	1.0635	137.6355
e	=	0.3	19.1552	1.5953	179.2045
E	=	0.4	23.7186	2.1270	220.7756
^К 3	=	10			
E	=	0	54.6529	0	544.9142
ŧ	=	0.04	56.4782	0.2127	561.5427
ŧ	=	0.08	58.3035	0.4254	578.1711
6	=	0.12	60.1289	0.6382	594.7995

Table A.2.4. (continued)

K ₃	=	20	ß ₂₁	B 26	ß 27
٤	=	0	109.3035	0	1089.8285
E	=	0.04	111.1311	0.2127	1106.4569
e	=	0.08	112.9564	0.4254	1123.0853
£	=	0.12	114.7817	0.6382	1139.7137

APPENDIX 3

VDFG generation curves

Figures A.3.1 to A.3.3.

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APPENDIX 4

PERFORMANCE RESPONSE FIGURE OF

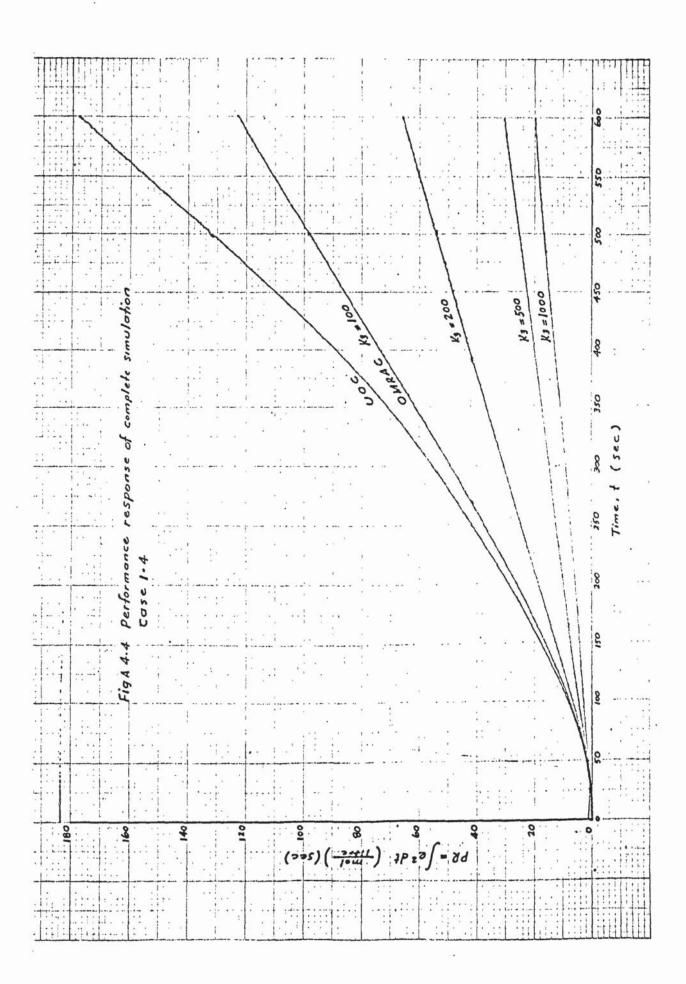
COMPLETE SIMULATION

Figures A.4.1. to A.4.21

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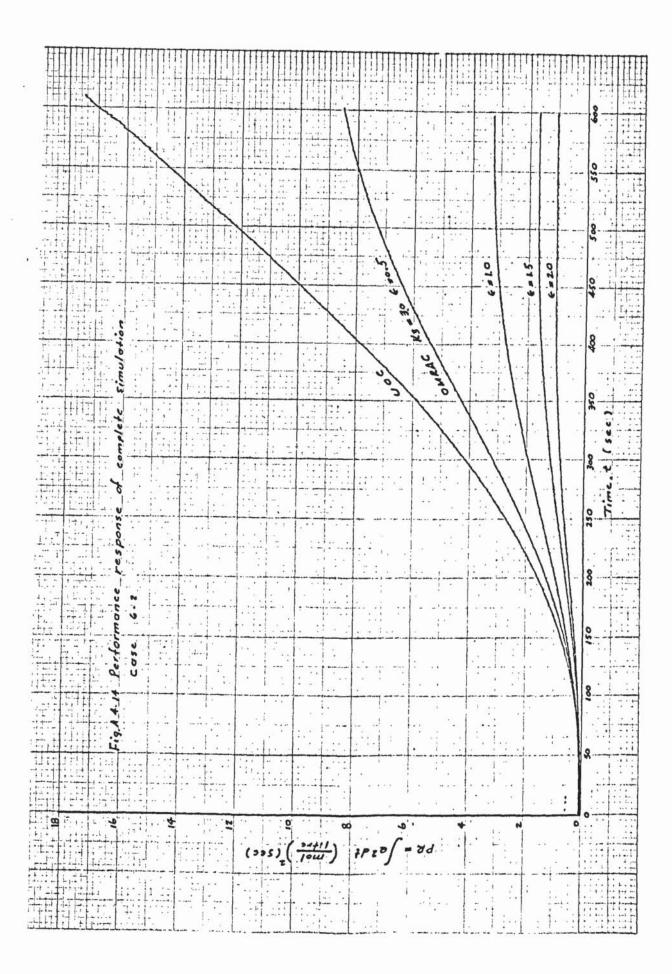
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APPENDIX 5

CALIBRATION OF MONITORING EQUIPMENT

AND INSTRUMENTS

Tables and corresponding Figures of calibration data:

Tables A.5.1 to A.5.16

Figures A.5.1 to A.5.19

Table A.5.1. Calibration of feed flowrate (F) rotameter

Tube size: 14s

Temperature 17°C

(see Figure A.5.1.)

Rotameter tube reading (cm)	Average flowrate litre/min
0	0.39
1	0.53
2	0.68
3	0.82
4	0.96
5	1.12
10	1.92
15	2.75
20	3.71
25	4.70

Table A.5.2. Calibration of cooling water rotameter.

Tube size : 17s
Temperature : 17°C

(see Figure A.5.2)

Rotameter tube reading (cm)	Average flowrate litre/min					
- 3	0.15					
- 2	0.45					
0	1.00					
1	1.29					
2	1.55					
3	1.83					
4	2.13					
5	2.45					
10	4.08					
15	5.81					
20	7.71					
23	8.91					

Table A.5.3. Calibration of flowmeter transmitter (see Fig.A.5.3)

Feed flowrate litre/min	Theoretical $\left[\begin{array}{c} \frac{F}{F_m} \end{array}\right]$ volt	$\left[\begin{array}{c} \text{Experimental} \\ \left[\begin{array}{c} F \\ F_m \end{array}\right] \text{ volt} \\ \end{array}\right]$
0	0	0.0
ı	2	2.20
2	4	4.10
3	6	6.00
4	8	7.90
5	10	9•75

Table A.5.4. Calibration of thermocouples

- 1. Feed Temperature, To to TR
- 2. Cooling water inlet temperature, T_{cl} to TR
- 3. Cooling water outlet temperature, $T_{\rm c}$ to TR
- 4. Reactor temperature, T to TRC used as TR (see Fig. A.5.4.)

	Thermo	couples	(mv)
1	2	3	4
0.0	0.0	0.0	0.0
1.0	1.0	1.0	1.0
4.1	4.1	4.1	4.1
	0.0	0.0 0.0	0.0 0.0 0.0

Table A.5.5. Calibration of temperature transmitters

- 1. Reactor temperature transmitter, $\left[\begin{array}{c} \frac{T}{T_m} \end{array}\right]$
- 2. Cooling water outlet temperature transmitter, $\begin{bmatrix} \frac{T_c}{T_m} \end{bmatrix}$

(see Fig. A.5.5)

Test temperature	Thermoo	ouples (m	$(T) \left[\frac{T}{T_m} \right]$ volt.	Tc Jvolt
°C	1	2	L T _m J volume	I T _m Jvoic.
0	0.0	0.0	0.0	0.0
25	1.0	1.0	2.5	2.5
100	4.1	4.1	10.0	10.0

Table A.5.6. Calibration of voltage to current (V/I) converter (Lec Dickens Model C5740) (see Fig.A.5.6.)

Voltage (input) (volt)	Current (output) (ma)
0	4.0
ı	5.45
2	7.05
3	8.90
4	10.50
5	12.10
6	13.80
7	15.50
8	17.00
9	18.50
10	20.00

Table A.5.7. Calibration of current to pneumatic pressure (I/P) transducer (Honeywell Model 31201/01) (see Fig.A.5.7.)

Current (input) (ma)	Pneumatic Pressure (output) (psig)
4.0	1
5.4	2
6.7	3
8.0	4
9.3	5
10.7	6
12.0	7
13.3	8
14.6	9
16.0	10
17.3	11
18.7	12
20.0	13

Table A.5.8. Calibration of combined V/I converter and I/P transducer (see Fig.A.5.8.)

voltage (input) (volt)	Pneumatic Pressure (output) (psig)	
0	1.00	
1	2.25	
2	3.48	
3	4.60	
4	5.85	
5	7.10	
6	8.30	
7	9.50	
8	10.70	
9	11.85	
10	12.80	

Table A.5.9. Calibration of control value flowrate vs. pneumatic pressure (without positioner)

(see Fig.A.5.9).

	Pneumatic pressure increasing		Pneumatic pressure decreasing	
Pneumatic Pressure	Flowrator	Flowrate	Flowrat or	Flowrate
(psig)	reading (cm)	(litre/min)	reading (cm)	(litre/min)
0	23.8	9.30	23.8	9.30
1.0	23.8	9.30	23.6	9.20
2.0	23.8	9.30	22.0	8.50
3.0	23.6	9.20	17.9	6.90
4.0	19.1	7.30	13.3	5.20
5.0	14.5	5.60	9.6	4.05
6.0	10.6	4.25	6.5	2.90
7.0	7.5	3.22	4.0	2.12
8.0	4.8	2.30	1.6	1.40
9.0	2.7	1.70	0.0	1.00
10.0	0.9	1.22	-1.2	0.60
11.0	-0.6	1.00	-2.8	0.20
12.0	-1.9	0.45	-3.0	0.15
13.0	-3.0	0.15	-3.0	0.15

Table A.5.10. Calibration of control valve positioner (Fig.A.5.10.)

	Pneumatic pressure increasing	Pneumatic pressure decreasing
Pneumatic pressure to positioner (psig)	Positioner output to control value (psig)	Positioner output to control valve (psig)
1.0	0	0
1.5	3.00	2.00
2.0	3.55	3.00
3.0	4.10	3.65
4.0	4.75	4.20
5.0	6.00	5.25
6.0	7.00	6.20
7.0	8.10	7.20
8.0	9.25	8.20
9.0	10.20	9.40
10.0	11.80	10.40
11.0	13.20	12.00
11.5	18.00	18.00

Table A.5.11. Calibration of control valve flowrate

vs. pneumatic pressure (with positioner)

(Fig.A.5.11)

	Pneumatic pressure increasing		Pneumatic pressure decreasing	
Pneumatic pressure on	Flowrator reading	Flowrate	Flowrator reading	Flowrate
control valve (psig)	(cm)	(litre/min)	(cm)	(litre/min)
1.0	23.9	9.30	23.8	9.30
1.5	23.0	8.95	22.8	8.85
2.0	21.7	8.40	21.5	8.35
3.0	17.5	6.70	17.3	6.65
4.0	13.6	5.30	13.4	5.25
5.0	10.4	4.20	10.3	4.20
6.0	7.5	3.28	7.4	3.26
7.0	5.3	2.55	5.1	2.50
8.0	3.5	2.00	2.7	1.75
9.0	1.0	1.30	0.7	1.20
10.0	-0.6	0.85	-0.6	0.80
11.0	-2.5	0.30	-2.5	0.30
11.5	-4.0	0	-4.0	0

Table A.5.12. Calibration of V/I converter input from TR-48, $\left\lceil \frac{F_{cg}}{F_{cm}} \right\rceil$ (volt), vs. control valve flowrate, F_{c} (litre/min) (with positioner)

(Fig. A.5.12)

*	voltage	e increasing	voltage d	ecreasing
[Fcg]	Rotameter reading	Flowrate . Fc	Rotameter reading	Flowrate Fc
(volt)	(cm)	(litre/min)	(cm)	(litre/min)
0	23.83	9.30	23.83	9.30
1.0	20.87	8.05	20.63	8.00
2.0	15.63	6.02	15.37	5.95
3.0	11.23	4.57	11.00	4.50
4.0	7.77	3.32	7.60	3.30
5.0	4.87	2.30	4.70	2.22
6.0	2.10	1.55	1.87	1.50
7.0	0.00	1.00	0.17	0.95
8.0	-2.00	0.,45	-2.17	0.40
9.0	-4.00	0.0	-4.00	0.0
10.0	-4.00	0.0	-4.00	0.0

Table A.5.13. Calibration of overall F_c interface system between $\left[\frac{F_c}{F_{cm}}\right]$ (volt) from hybrid computer and F_c (litre/min) from control valve (with positioner) (Fig.A.5.14)

$\begin{bmatrix} \frac{F_c}{F_{cm}} \end{bmatrix}$ before	$\begin{bmatrix} \frac{F_{\text{cg}}}{F_{\text{cm}}} \end{bmatrix}$ after VDFG	Theoretical $ \left[\begin{array}{c} F_{\text{cg}} \\ F_{\text{cm}} \end{array} \right] $ value	Rotameter reading	Control valve flowrate
(volt)	(volt)	(volt)	(cm)	(litre/min)
0	8.884	9.00	-4.0	0
1.0	6.782	6.90	0.01	1.01
2.0	5.304	5.41	3.60	2.02
3.0	4.192	4.30	6.80	3.02
4.0	3.290	3.38	9.80	4.04
5.0	2.554	2.62	12.60	4.98
6.0	1.970	2.03	15.20	5.95
7.0	1.544	1.58	17.60	6.95
8.0	1.012	1.01	20.40	7.90
9.0	0.264	0.25	23.20	9.00
9.3	0.050	0.0	23.90	9.30

Table A.5.14. Calibration of computer output $\left[\frac{Q_{gg}}{Q_{gm}}\right]$ vs. variac position (Fig.A.5.15).

Variac position VR	$\left[\begin{array}{c} \frac{Q_{\text{gg}}}{Q_{\text{gm}}} \\ \text{volt} \end{array}\right]$	$\left[\begin{array}{c} \frac{Q}{Q_{\text{gg}}} \\ \end{array}\right]_{\text{volt}}$
10	0.80	0.064
20	1.60	0.276
30	2.46	0.605
40	3.26	1.063
50	4.11	1.689
60	5.05	2.550
70	6.13	3.756
. 80	7.44	5.535
85	8.23	6.773

Table A.5.15. Calibration of variac position vs heat output from immersion heater, Q_g (Fig.A.5.16) $Q_g = 0.06 \text{ F}\Delta T \text{ (Kcal x 10}^3/\text{h)} \text{ (equation (8-2))}$

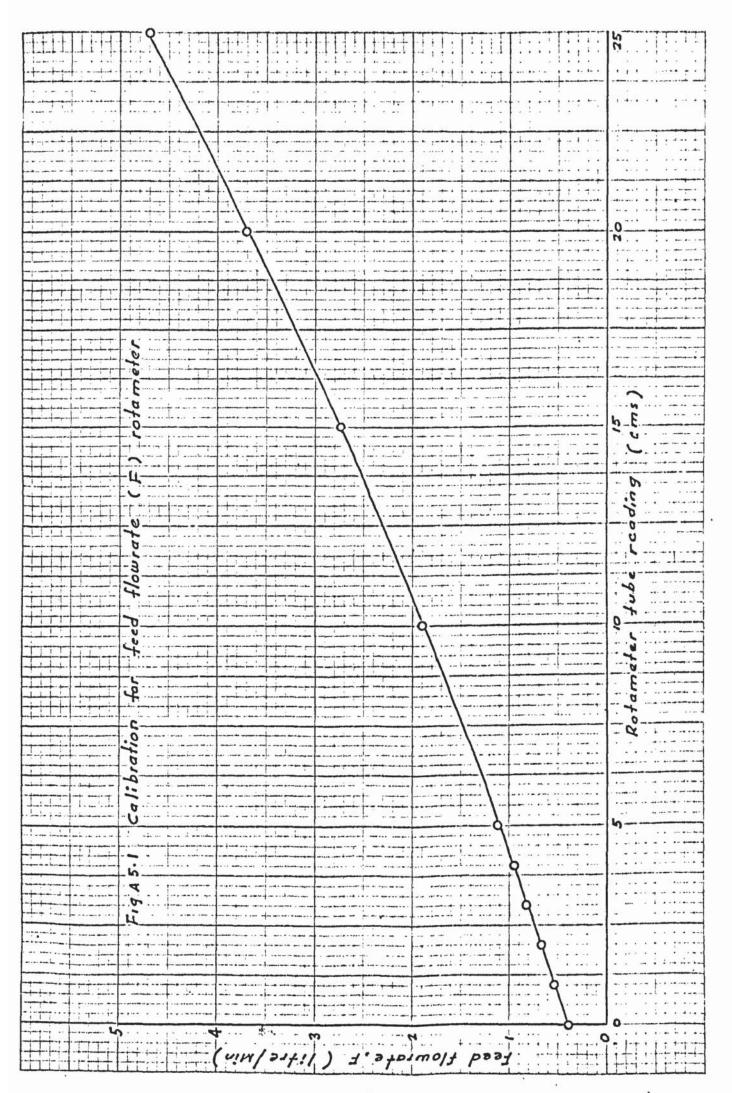
Feed flow-	Variac position	ΤΔ	Q_g	T	Q_g	(Qg)av	
rate (litre/ min)	(VR)	(°C)	Kcalx10	3 - °C	Kcalx103	Kcalx10 ³	
3	10	0.30	0.054	0.50	0.09	0.072	
3	20	1.90	0.342	2.30	0.414	0.378	
3	30	4.90	0.828	5.10	0.918	0.873	
3	40	8.50	1.530	9.15	1.647	1.588	
3	50	13.50	2.430	14.05	2.529	2.479	
3	60	19.90	3.582	20.0	3.600	3.591	
5	7C	16.40	4.920	16.70	5.010	4.965	
5	80	21.30	6.390	21.85	6.555	6.472	
5	85	24.50	7.350	24.50	7.350	7.350	

Note:

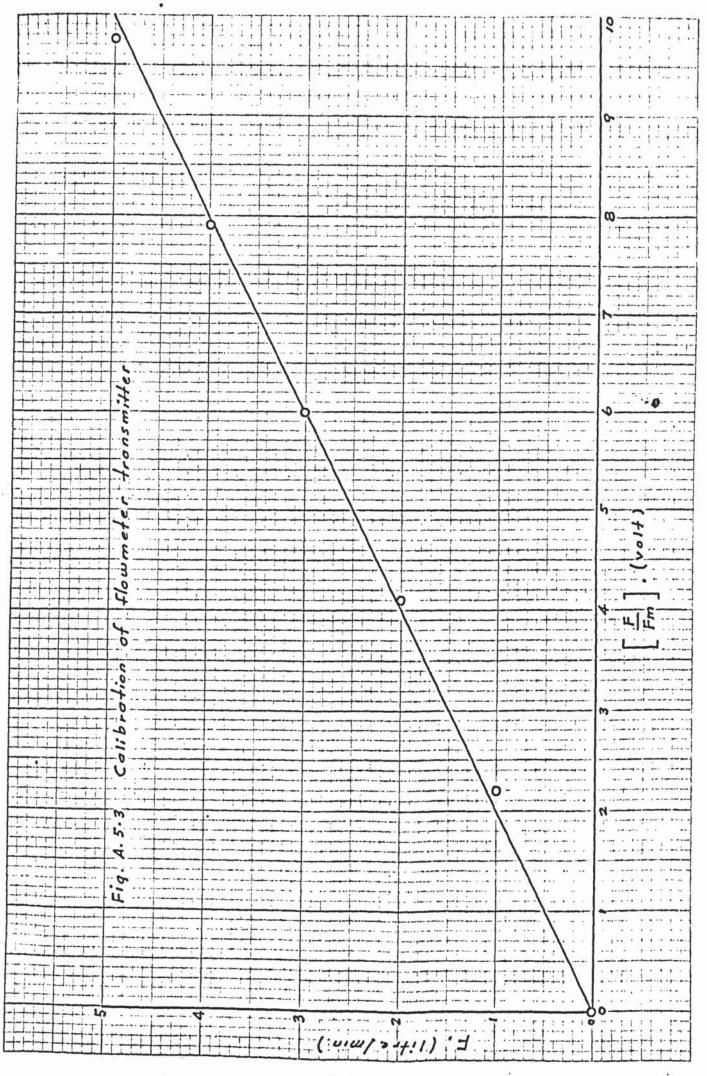
- 1. From columns 2 and 3 in Table A.5.14 and columns 4 and 6 in Table A.5.15 to plot Figure A.5.17.
- From column 2 in Table A.5.14 and column 7 in Table A.5.15 to plot Figure A.5.18.

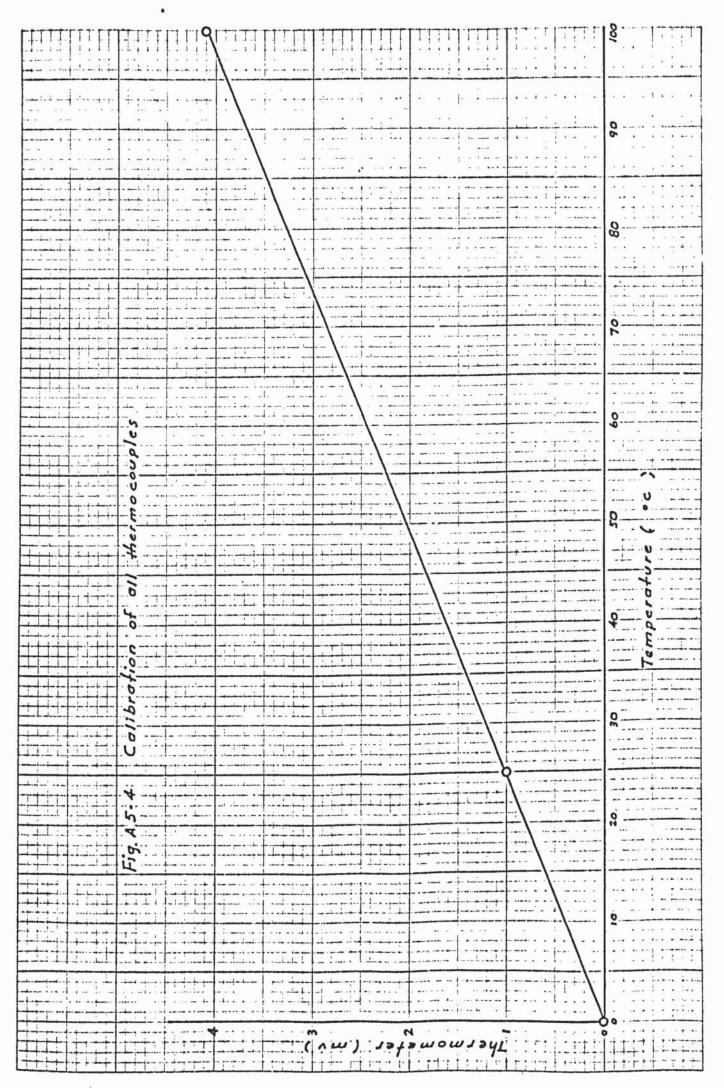
Table A.5.16. Calibration of overall heat generation, Q_g interface system between $\left[\begin{array}{c}Q_g\\Q_{gm}\end{array}\right]$ (before DFG) Vs. Q_g (from immersion heater) (Fig.A.5.19)

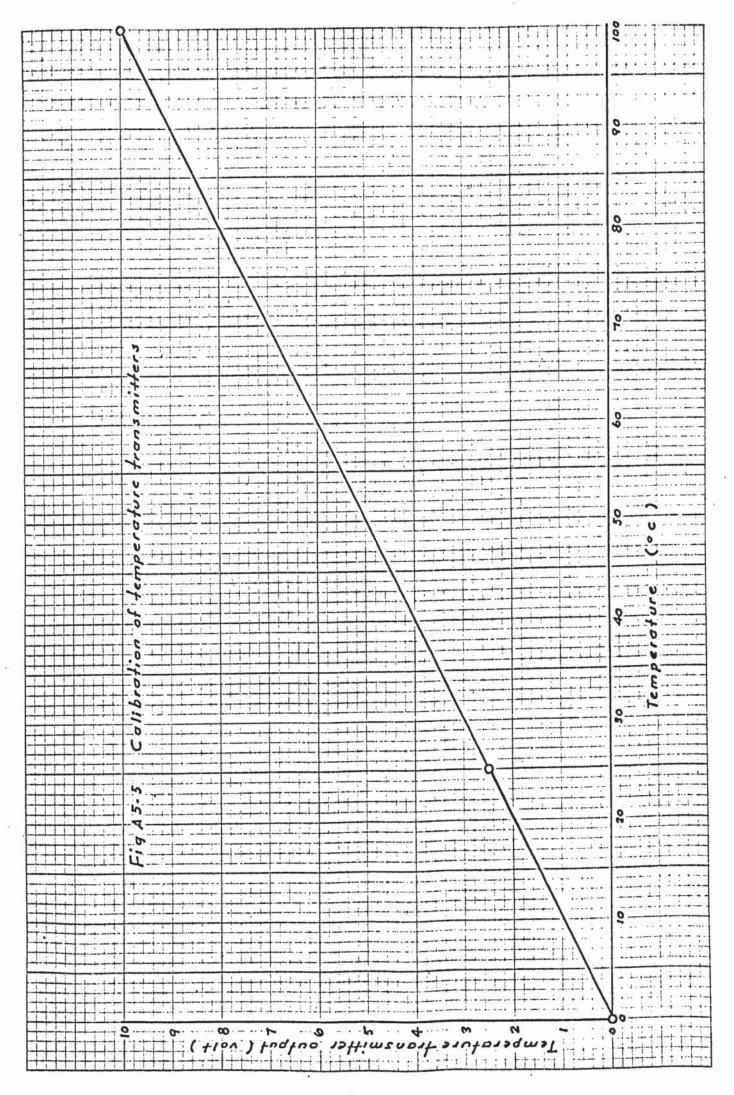
$\left[\frac{Q_g}{Q_{gm}}\right]$	$\left[\begin{array}{c} Q_{gg} \\ \overline{Q}_{gm} \end{array}\right]$	Variac position	Т	F	Q _E
before DFG (volt)	after DFG (volt)	(VR)	(°c)	litre min	Kcalx10 ³
1.0	2.65	32.6	5.7	3	1.026
2.0	3.66	45.0	11.2	3	2.016
3.0	4.59	55.3	17.2	3	3.096
4.0	5.39	63.3	22.8	3	4.065
5.0	6.16	71.0	17.0	5	5.101
6.0	7.04	78.0	20,3	5	6.090
7.0	7.94	83.6	23.6	5	7.080
8.0	8.79	88.0	26.9	5	8.070
7.0	7.94	83.2	23.9	5	7.170
6.0	7.07	77.5	20.6	5	6.180
5.0	6.15	70.2	. 17.0	5	5.100
4.0	5.39	63.3	22.6	3	4.068
3.0	4.58	55.2	17.6	3	3.160
2.0	3.66	45.0	11.4	3	2.050
1.0	2.65	32.5	6.1	3	1.090

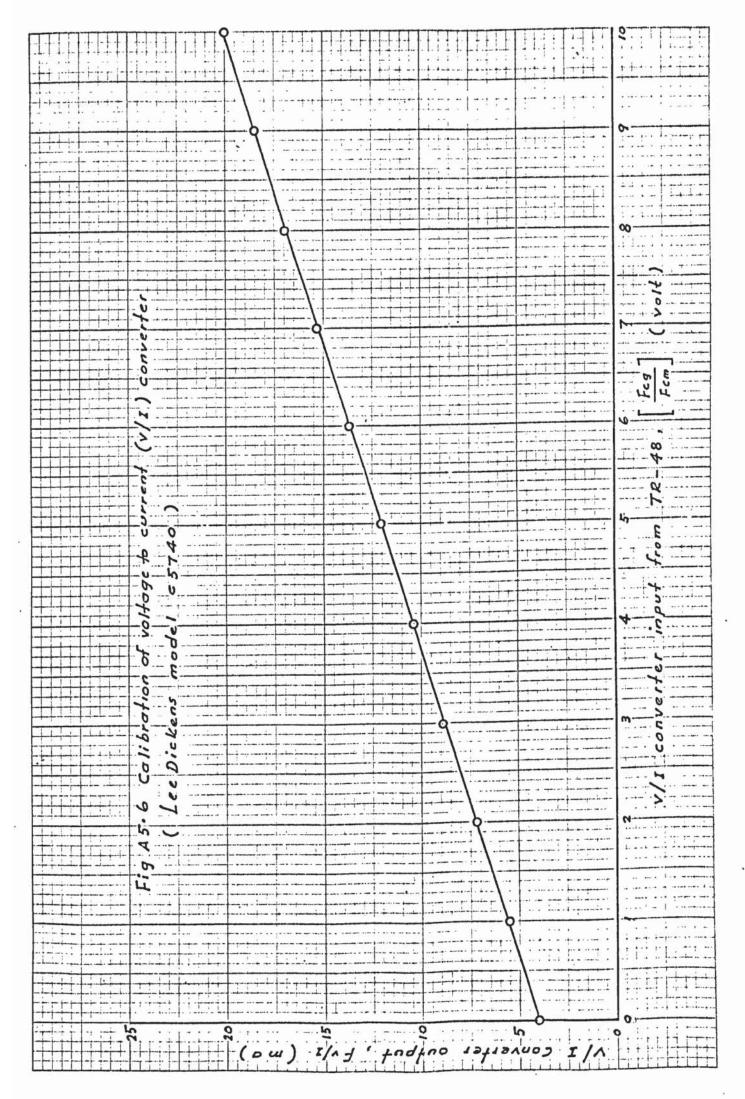


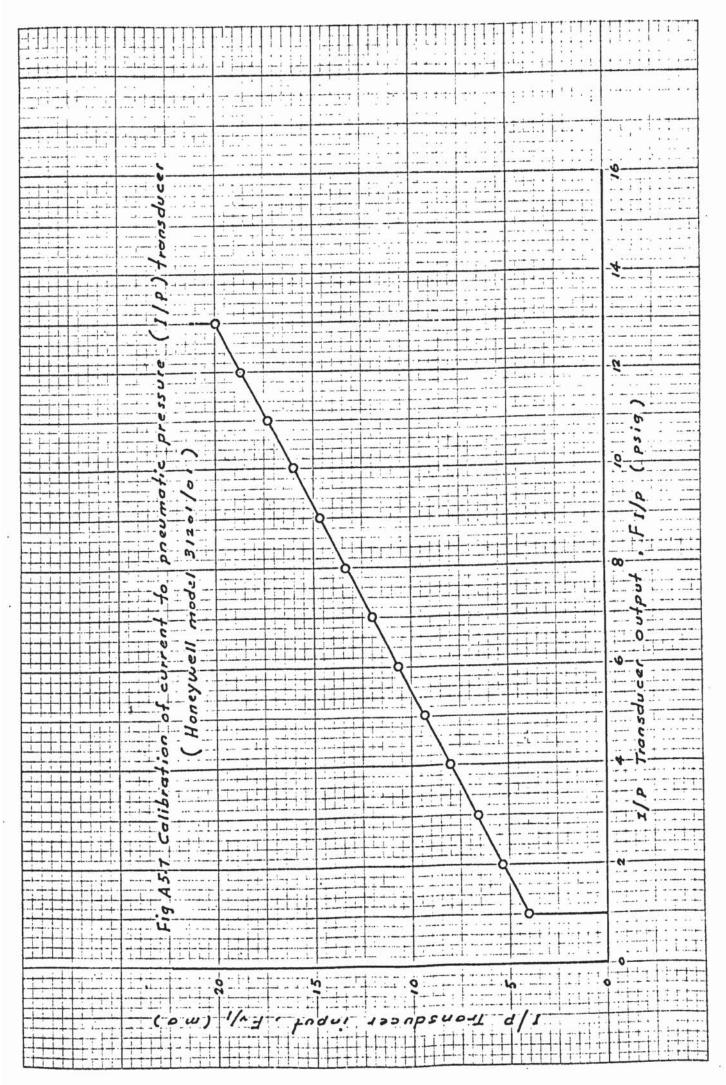
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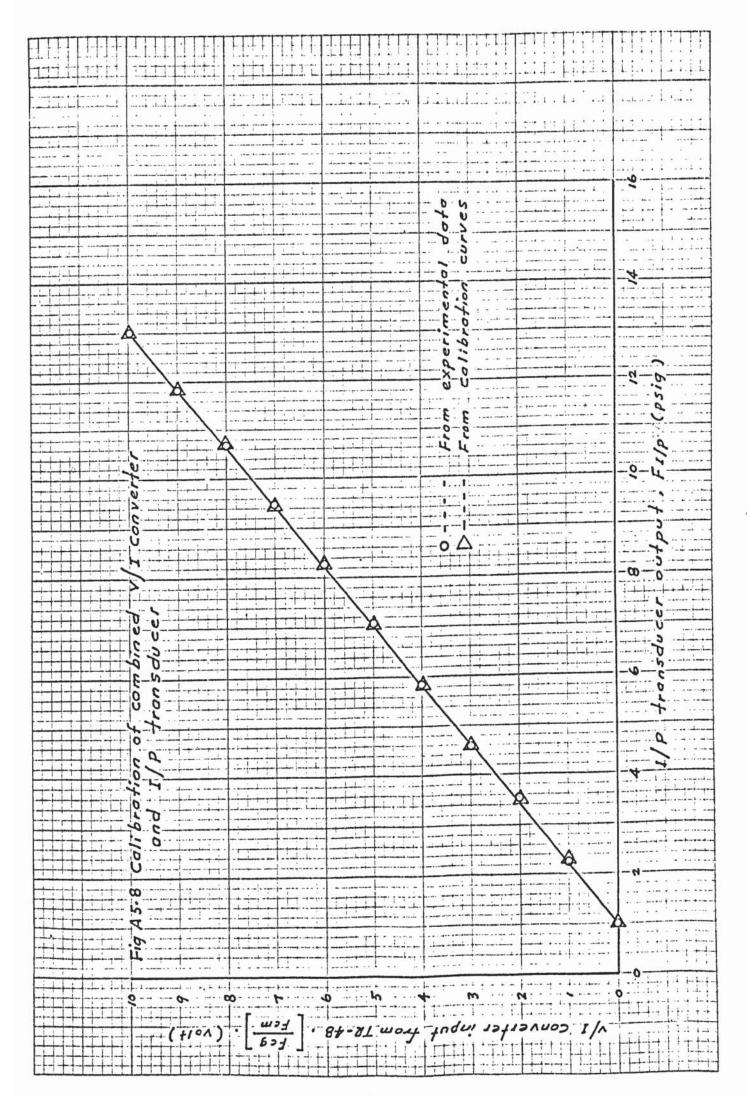






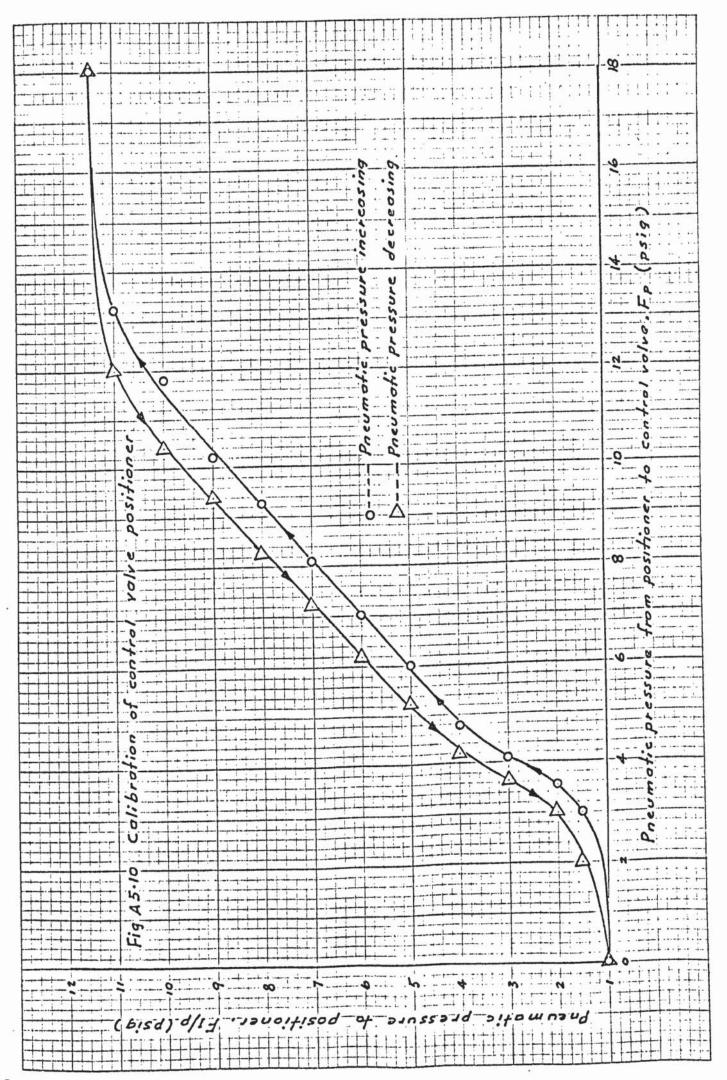




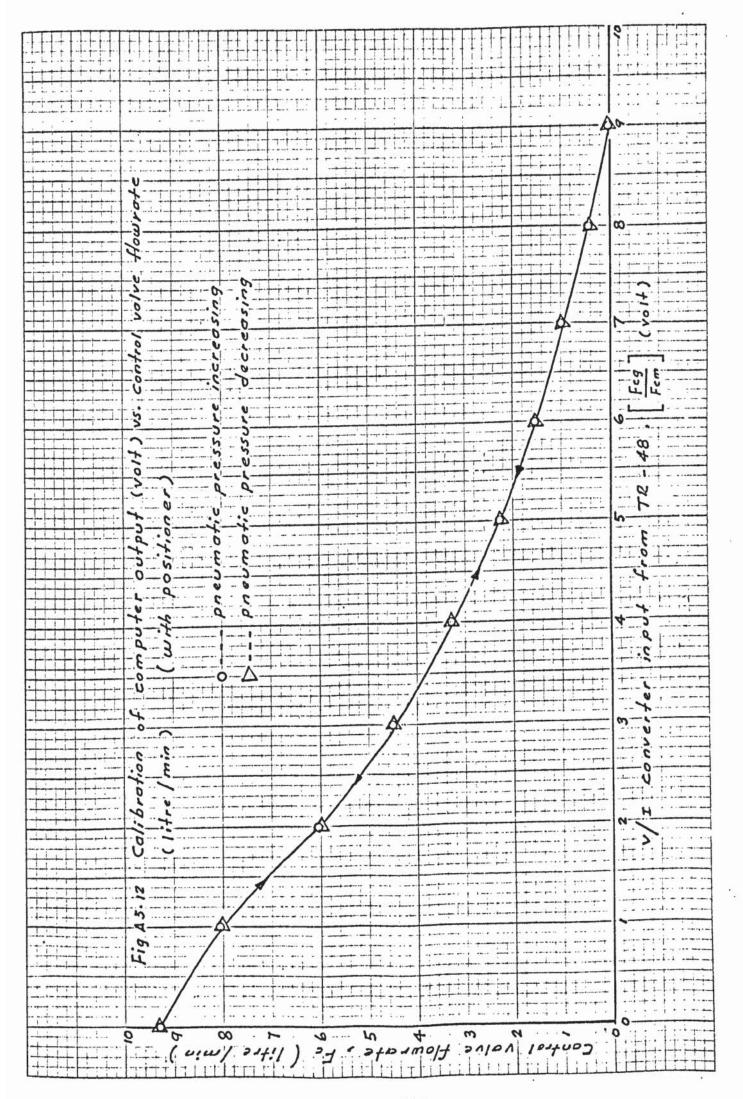


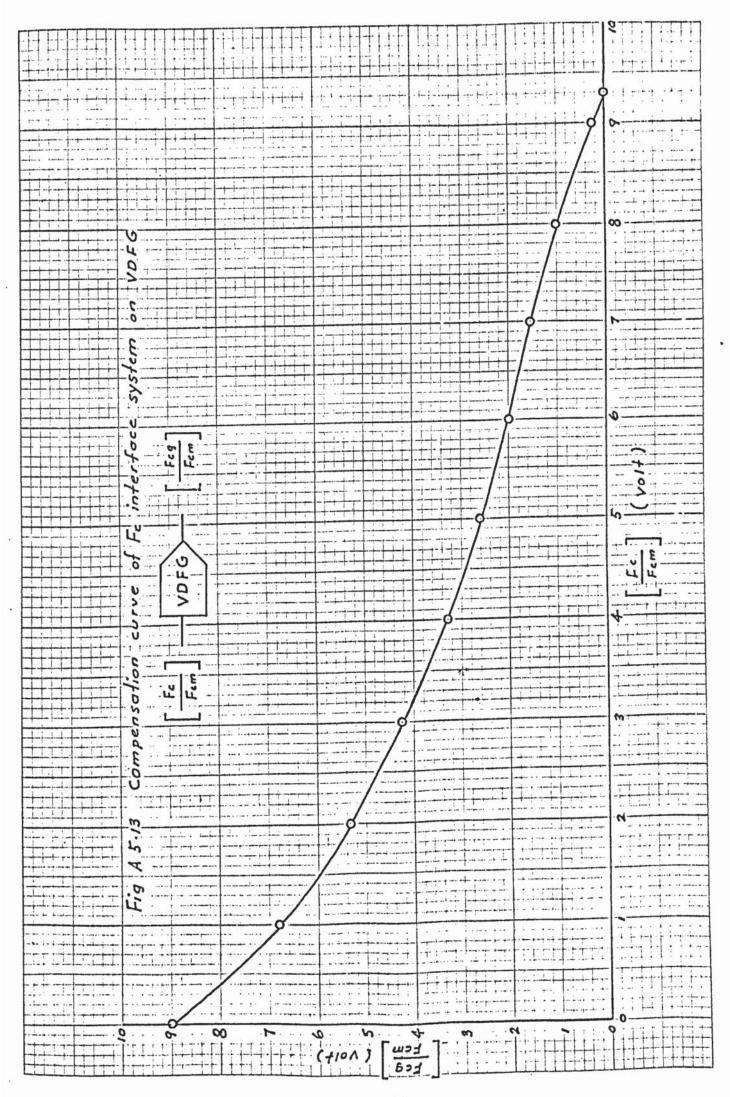
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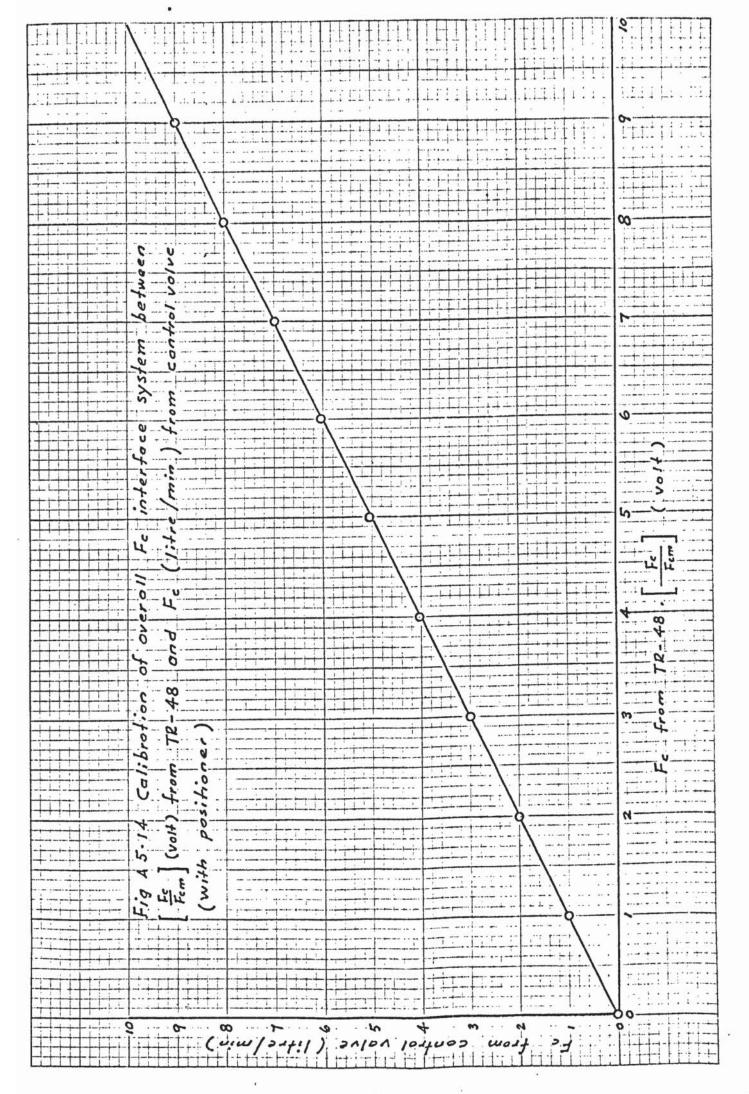
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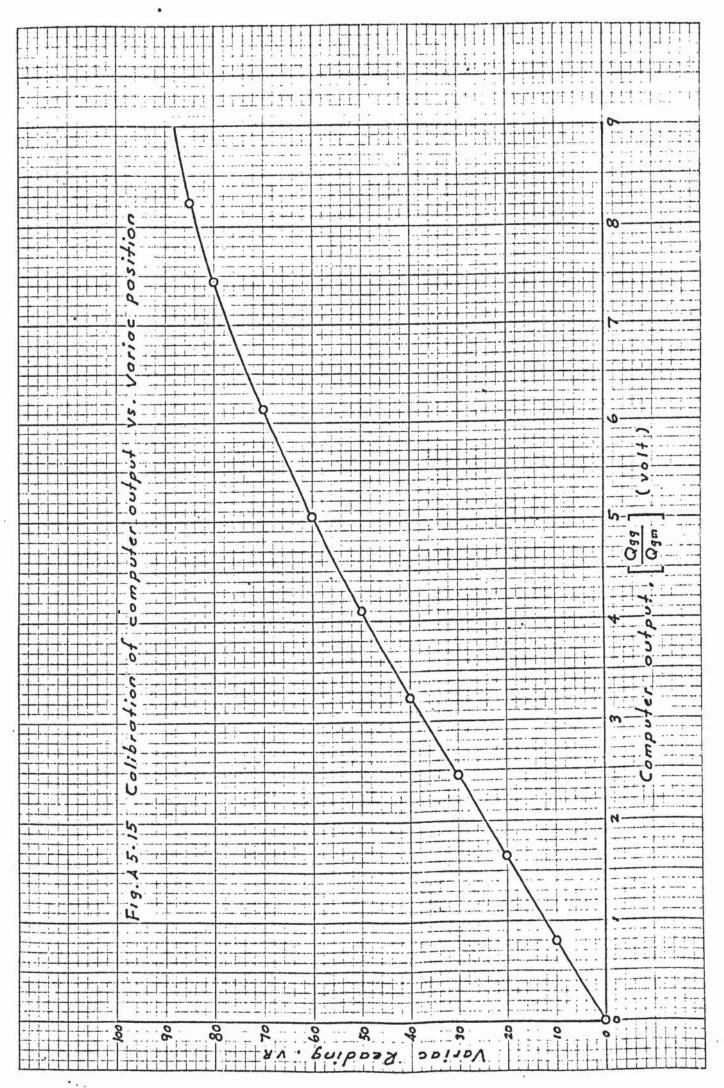


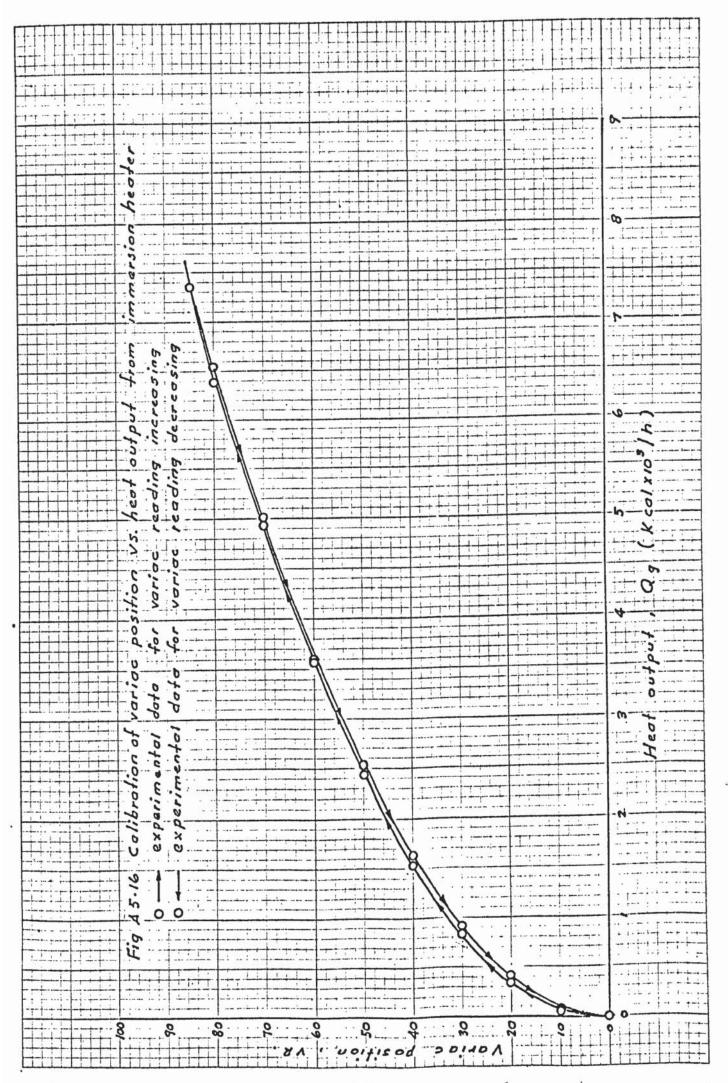
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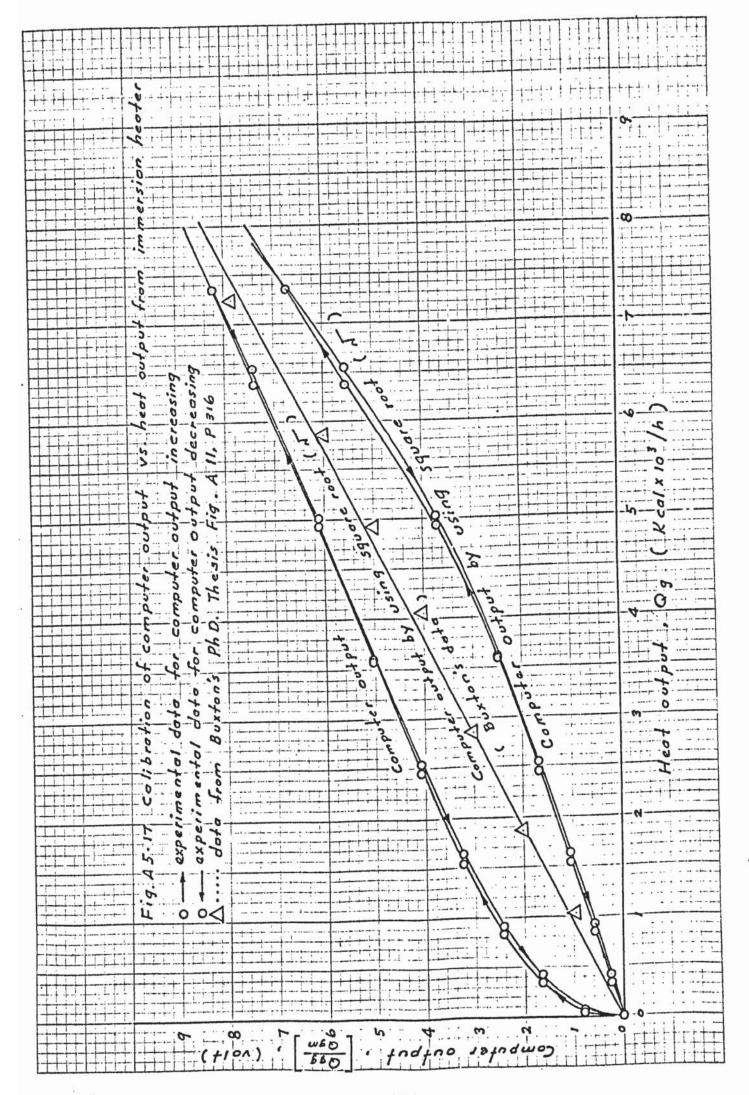


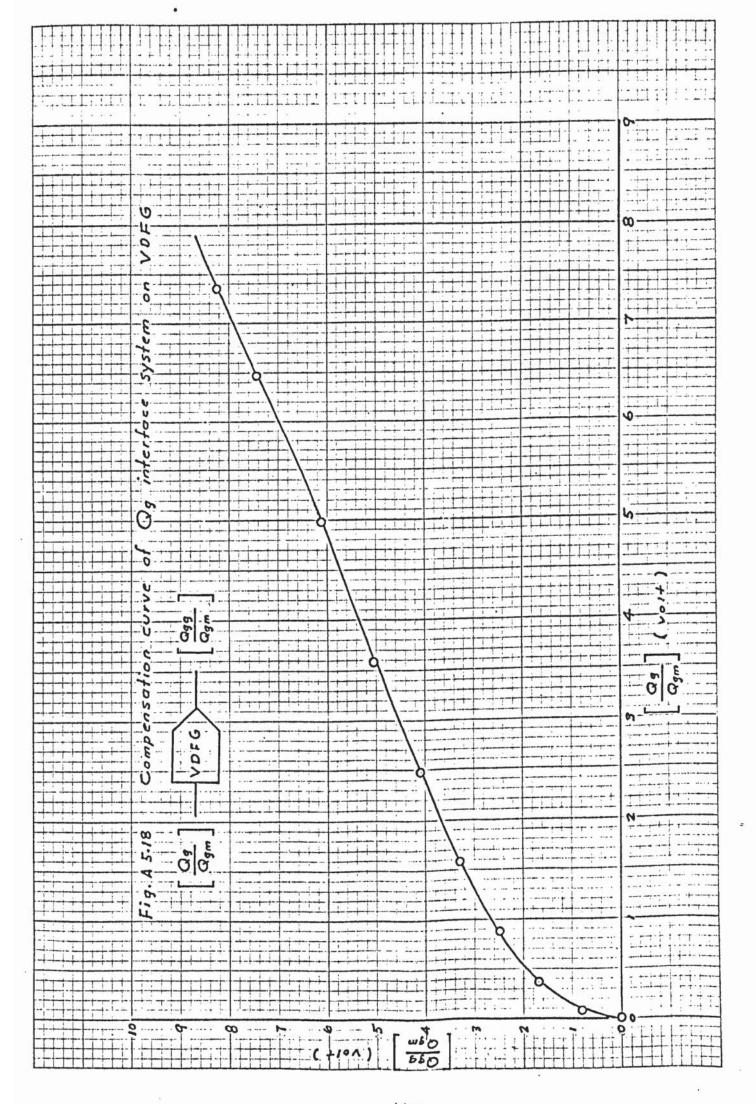


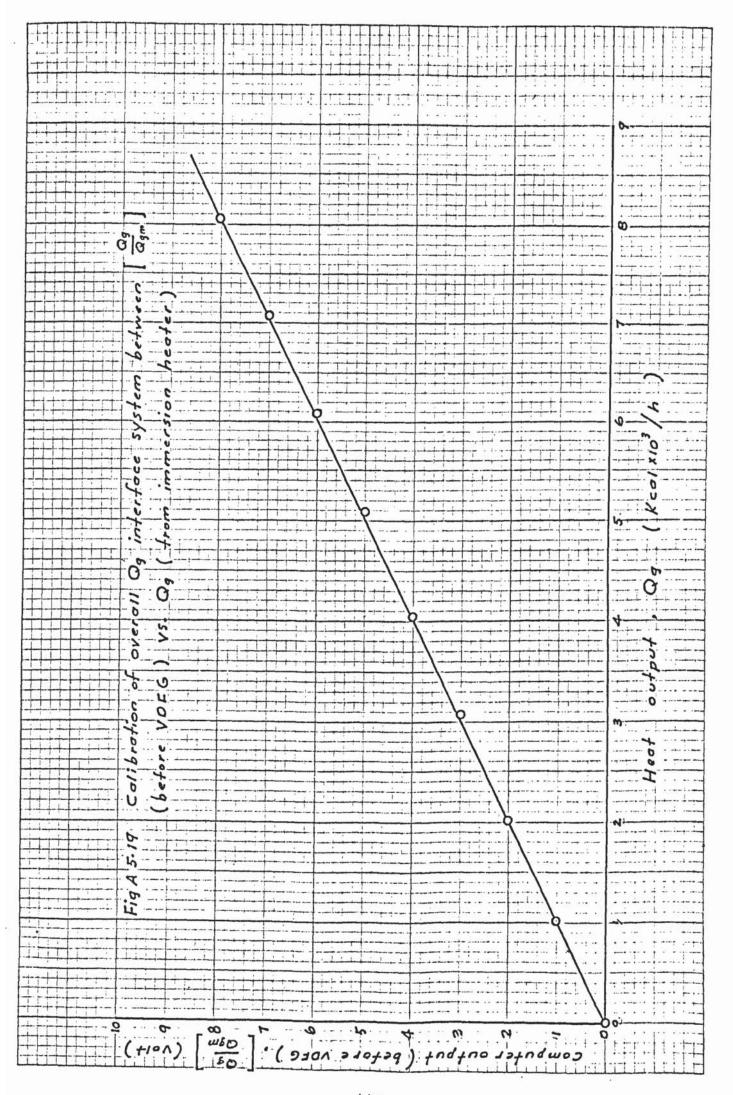












APPENDIX 6

Experimental data at final steady

state of on-line operation

Tables A.6.1 to A.6.10.

Table A.6.1. Final steady state conditions of on-line operation for cases 1.1 and 1.2

		m	A M	r	ជ	C	(aKC)	Variac
	T _i °C	T °C	ΔT _c °C	litre min	litre min	mol litre	mu	VR
Case 1.1							*****	
US	20.0	31.45	9.5	2.7	2.0	.075	.0278	54.0
UOC	20.0	30.70	10.0	2.7	2.0	.084	.0270	53.5
OMRAC								
K ₃ =100	20.0	30.60	10.3	2.7	2.0	.087	.0278	54.0
K ₃ =200	20.0	30.50	10.5	2.7	2.0	.087	.0278	54.0
K ₃ =500	20.0	30.40	10.2	2.7	2.1	.088	.0278	54.0
K ₃ =1000	20.0	30.30	10.0	2.7	2.1	.089	.0278	54.0
Case 1.2								
US	19.0	31.4	10.0	2.4	1.9	.079	.0278	54.5
UOC	19.0	30.7	10.3	2.4	2.0	.086	.0278	54.5
OMRAC								
K ₃ =100	19.0	30.5	10.8	2.4	2.0	.088	.0278	54.2
У К ₃ =200	19.0	30.5	10.6	2.4	2.0	.088	.0278	54.2
) K ₃ =500	19.0	30.4	10.5	2.4	2.1	.088	.0278	54.0
K ₃ =1000	19.0	30.4	10.5	2.4	2.1	.089	.0278	54.0

Notes:

- F before change is 3.0 litre/min
- 2. Conditions of operating cases are shown in Table 10.1

3. (aKC)
$$\left[\frac{a}{a_{m}}\right]\left[\frac{K}{K_{m}}\right]\left[\frac{C}{C_{m}}\right]$$

All above notes apply also to the following tables:

Table A.6.2. Final steady state conditions of on-line operation for Cases 1.3 and 1.4

								1-1-12/2
	T _i	T	ΔT_{c}	F	Fc	С	(aKC)	Variac
	o C	°C	°C	litre min	litre min	mol litre	mu	VR
0 2-7								
Case 1.3	20.5	32.70	8.6	2.7	1.80	.0560	.0270	53.5
UOC	20.5	31.40	9.5	2.7	2.10	.0750	.0276	54.0
OMRAC:	2							
K ₃ =100	20.5	31.00	9.2	2.7	2.30	.0810	.0278	54.3
K ₃ =200	20.5	30.80	9.1	2.7	2.40	.0830	.0278	54.0
K ₃ =500		30.60	9.0	2.7	2.50	.0860	.0280	54.2
K ₃ =1000	20.5	30.50	8.8	2.7	2.60	.0875	.0280	54.2
K ₃ =4000	20.5	30.40	8.6	2.7	2.70	.0890	.0280	54.2
Case 1.4					2222	01:00	.0240	51.0
US	19.0	32.80	12.0	2.4	0.70	.0420		
UOC	18.5	32.10	11.5	2.4	1.20	.0550	.0268	53.0
OMRAC:								
K ₃ =100	18.5	31.00	12.4	2.4	1.50	.0770	.0272	53.4
	NAME OF THE OWNER, OF THE OWNER, OF THE OWNER, OF THE OWNER, OWNER, OWNER, OWNER, OWNER, OWNER, OWNER, OWNER,		0	2.4	1.55	.0780	.0278	54.5
	18.0	30.50	11.8					
K ₃ =200 K ₃ =500	18.0 18.0	30.50	11.0	2.4	1.75	.0820	.0278	54.5

Table A.6.3. Final steady state conditions of on-line operation for Cases 2.1, 2.2 and 2.3

	T _i	Т	ΔT _c	F	Fc	C	(aKC)	Variac
	°C	°c	°C	litre min	litte min	mol litre	mu	VR
Case 2.1							•	
US	22.0	29.80	8.1	3.3	3.60	.1070	.0310	57.0
UOC	22.0	30.35	8.5	3.3	3.20	.1020	.0310	57.0
OMRAC:								
K ₃ =100	22.0	30.70	8.6	3.3	3.10	.0990	.0310	57.0
K ₃ =200	22.0	30.90	8.6	3.3	3.10	.0960	.0310	57.0
K ₃ =500	22.0	31.10	8.8	3.3	2.90	.0940	.0310	57.0
K ₃ =1000	22.0	31.20	9.2	3.3	2.70	.0930	.0310	57.0
Case 2.2								
US	21.5	29.50	8.8	3.6	3.50	.1180	.0330	59.0
UOC	21.5	30.40	9.2	3.6	3.07	.1110	.0330	59.0
OMRAC:								
K ₃ =100	21.5	30.70	9.2	3.6	2.90	.1050	.0330	59.0
K ₃ =200	21.5	31.00	9.2	3.6	2.74	.1020	.0330	59.0
K ₃ =500	21.5	31.10	10.3	3.6	2.40	.0990	.0330	59.0
K ₃ =1000	21.5	31.20	10.3	3.6	2.40	.0960	.0330	59.0
Case 2.3		9						
US	21.5	30.50	9.4	3.6	2.90	.1092	.0330	59.0
UOC	21.5	31.00	10.1	3.6	2.50	.1000	.0330	59.0
OMRAC:								
K = 100	21.5	31.20	10.1	3.6	2.50	.0970	.0330	59.0
K = 200	21.5	31.30	10.2	3.6	2.40	.0960	.0330	59.0
K = 500	21.5	31.40	10.2	3.6	2.40	.0940	.0330	59.0
K = 1000	21.5	31.50	10.3	3.6	2.30	.0930	.0330	59.0

Table A.6.4. Final steady state conditions of on-line operation for Cases 3.1, 3.2 and 3.3.

	°C Ti	T °C	Δ ^T c °C	F litre min	Fc litre min	C mol litre	(aKC)	Variac VR
Case 3.1.								
บร	21.5	30.40	10.4	3.0	2.00	.1075	.0278	54.5
UOC	21.5	31.20	10.2	3.0	2.00	.1010	.0278	54.5
OMRAC :								
K ₃ =100	21.5	31.40	10.0	3.0	2.00	.0980	.0278	54.3
K ₃ =200	21.5	31.40	13.2	3.0	1.44	.0980	.0278	54.5
K ₃ =500	21.5	31.50	13.2	3.0	1.44	.0940	.0278	54.5
K ₃ =1000	21.5	31.60	13.3	3.0	1.40	.0932	.0278	54.5
Case 3.2.								
US	22.0	30.50	10.5	3.0	2.20	.1210	.0270	53.0
UOC	22.0	31.40	12.4	3.0	1.70	.1112	.0276	54.0
OMRAC :	045							
K ₃ =100	22.0	31.70	13.0	3.0	1.58	.1084	.0278	54.3
K ₃ =200	22.0	31.70	13.0	3.0	1.55	.1040	.0278	54.5
K ₃ =500	22.0	32.00	15.6	3.0	1.20	.1014	.0278	54.5
K ₃ =1000	22.0	32.40	16.1	3.0	1.11	.0990	.0278	54.5
Case 3.3.		·····						
US	22.0	30.55	10.5	3.0	2.20	.1330	.0276	54.0
UOC	22.0	31.65	13.2		1.50	.1194	.0276	54.0
OMRAC :								
K ₃ =100	22.0	32.05	14.0	3.0	1.36	.1240	.0278	54.4
) K ₃ =200	22.0	32.45	15.0	3.0	1.18	.1096	.0278	54.4
У К ₃ =500	22.0	32.80	15.6	3.0	1.10	.1034	.0278	54.4
K ₃ =1000	22.0	33.25	16.0	3.0	1.00	.0988	.0280	54.9

Table A.6.5. Final steady state conditions of on-line operation for Cases 4.1 and 4.2

	Ti	т	ΔTc	F	Fc	C	(aKC)	Variac
	· °C	°c		litre min	litre min	mol litre	mu	VR
Case 4.1								
US	21.5	31.00	11.0	3.3	2.20	.1140	.0310	57.0
UOC	21.5	31.80	12.0	3.3	1.80	.1030	.0310	57.0
OMRAC :								
K ₃ =100	21.5	32.00	12.0	3.3	1.70	.0980	.0310	57.2
K ₃ =200	21.5	32.10	12.5	3.3.	1.60	.0970	.0310	57.2
K ₃ =500	21.5	32.20	13.6	3.3	1.50	.0960	.0314	57.5
K ₃ =1000	21.5	32.30	13.6	3.3	1.50	.0940	.0314	57.5
K ₃ =4000	21.5	32.40	13.6	3.3	1.50	.0920	.0314	57•5
Case 4.2.								
US	21.0	29.60	11.2	3.3	2.30	.1240	.0308	57.0
UOC	21.0	30.70	13.5	3.3	1.64	.1120	.0308	57.0
OMRAC :								
K ₃ =100	21.0	31.20	14.0	3.3	1.50	.1058	.0310	57.0
K ₃ =200	21.0	31.30	14.6	3.3	1.40	.1025	.0310	57.2
K ₃ =500	21.0	31.50	14.8	3.3	1.30	.0980	.0310	57.2
K ₃ =1000	21.0	31.70	15.2	3.3	1.25	.0945	.0310	57.3
K ₃ =4000	21.0	31.90	15.9	3.3	1.15	.0930	.0310	57•5

Table A.6.6. Final steady state conditions of on-line operations for Cases 5.1, 5.2 and 5.3

	T _i	T	ΔT _c	F	Fc	С	(aKC)	Variac
	°C	°C	°c	litre min	litre min	mol litre	mu	VR
Case 5.1.								
OMRAC								
K ₃ = 100					×			
6 = 0	21.0	31.50	13.0	3.3	1.60	.1050	.0310	57.0
e = 1	21.0	32.30	14.5	3.3	1.30	.0980	.0310	57.0
£ = 2.	21.0	32.40	13.4	3.3	1.40	.0924	.0310	57.0
6 = 3	21.0	32.50	15.5	_3.3	1.20	.0890	.0310	57.0
Case 5.2								
OMRAC								
K ₃ = 100								
6 = 0	21.0	31.60	15.0	3.3	1.30	.1050	.0310	5 7•5
£ * 0.2	21.0	31.90	15.6	3.3	1.20	.0980	.0310	57.5
E = 0.4	21.0	32.20	16.3	3.3	1.10	.0930	.0310	57.5
6 = 0.6	21.0	32.30	16.2	3.3	1.10	.0914	.0310	57.5
6 = 0.8	21.0	32.40	16.8	3.3	1.00	.0910	.0310	57.5
e = 1.0	21.0	32.40	16.8	3.3	1.00	.0912	.0310	57•5
Case 5.3								
OMRAC								
K ₃ = 200								
e = 0	21.0	31.70	13.2	3.3	1.50	.1016	0510 .	57.0
6 = 0.2	21.0	31.95	14.2	3.3	1.40	.0980	.0310	57.0
6 = 0.4	21.0	32.00	14.3	3.3	1.30	.0945	.0310	57.0
€ = 0.6	21.0	32.40	14.5	3.3	1.30	.0934	.0310	57.0
£ = 0.8	21.0	32.40	15.0	3.3	1.20	.0930	.0310	57.0
e = 1.0	21.0	32.50	15.2	3.3	1.20	.0920	.0310	57.
*			1 -1					

Table A.6.7. Final steady state conditions for the on-line operations for Cases 6.1, 6.3 and 6.5

				0.00				
	Ti	T	ΔTc	F	Fc	С	(aKC)	Variac
	°C	°C	°c	litre min	litre min	mol litre	mu	VR
0 (1								
Case 6.1		71 10	1/1 5	3.3	1.69	.1100	.0310	57.5
UOC	22.0	31.10	14.5	2.2	1.0)	,	,	
OMRAC								
$K_3 = 1.0$						ERROR - News		
£ = 0.1	22.5	32.30	15.0	3.3	1.50	.0940	.0310	57•5
6 = 0.2	22.5	32.70	16.0	3.3	1.38	.0860	.0310	57.5
e = 0.3	22.5	32.60	16.0	3.3	1.35	.0870	.0310	57.5
€ = 0.4	22.5	32.50	15.0	3.3	1.48	.0890	.0310	57•5
Case 6.3								
UOC	20.0	31.20	10.7	3.3	1.65	.1090	.0310	57.2
	20,0	,		5 (5)				
OMRAC			<u>.</u>					
$K_3 = 10$		= 2			. (0	1050	.0310	57.4
€ = 0	20.0	31.50	10.7	3.3	1.60	.1050		
€ = 0.04	20.0	31.80	11.5	3.3	1.40	.0990	.0310	57•4
e = 0.08	20.0	32.00	12.3	3.3	1.30	.0970	.0310	57.4
6 = 0.12	20.0	32.20	12.7	3.3	1.20	.0936	.0310	57.4
Case 6.5.					pallo collo		•	
	20.0	X1 10	11.0	3.3	1.64	.1098	.0310	57.2
UOC	20.0	31.10	11.0	7.7		. N = 1575 157. (5 .1872)	WAS TIES.	
OMRAC			0.00					
$K_3 = 20$,	220-	0710	57 h
6 = 0	20.0	31.70	11.9	3.3	1.40	.0980	.0310	57.4
$\epsilon = 0.04$	20.0	31.90	11.5	3.3	1.35	.0950	.0310	
e = 0.08	20.0	31.95	12.0	3.3	1.30	.0940	.0310	57.4
e = 0.12	20.0	32.00	12.8	3.3	1.20	.0925	.0310	57.4

Table A.6.8. Final steady state conditions of the on-line operations for Cases 7.1, 7.2 and 7.3.

**	T _i	T	ΔTc	F litre	F _c	C mol	(aKC)	Variac
	°c	°C ·	°C°	min	min	litre	mu	٧R
Case 7.1								
us	21.0	28.90	9.3	3.3	3.15	.1420	.0310	57.0
UOC.	21.0	30.80	11.3	3.3	1.95	.1200	.0310	57.4
OMRAC :								9
K ₃ = 100	21.0	31.20	12.0	3.3	1.75	.1150	.0310	57.4
K ₃ =200	21.0	31.50	13.0	3.3	1.55	.1100	.0310	57 '+
K ₃ =500	21.0	31.90	13.8	3.3	1.40	.1040	.0310	57.4
K ₃ =1000	21.0	32.10	14.4	3.3	1.20	.1010	.0310	57.4
Case 7.2								
US	21.6	29.20	12.0	3.3	2.00	.1330	.0276	54.0
UOC	21.6	30.90	13.4	3.3	1.50	.1145	.0280	54.5
OMRAC								
K ₃ =100	22.0	31.30	14.7	3.3	1.45	.1090	.0290	55.5
K ₃ =200	22.0	31.70	15.4	3.3	1.35	.1050	.0290	55.5
K ₃ =500	22.0	32.10	15.9	3.3	1.25	.1000	.0290	55.5
K ₃ =1000	22.0	32.30	16.2	3.3	1.10	.0970	.0290	55•5
Case 7.3	5							
US	21.5	30,20	10.7	3.3	2.30	.1222	.0300	56.5
noc	21.5	31.20	12.9	. 3.3	1.72	.1100	.0310	57.0
OMRAC								
K ₃ =100	21.5	31.80	13.2	3.3	1.70	.1020	.0310	57.0
K ₃ =200	21.5	31.72	13.5	3.3	1.65	.0960	.0310	57.0
-	21.5	31.84	1 45	3.3	1.50	.0950	.0310	57.0
K ₃ =1000	21.5	32.00	1 47	3.3	1.40	.0940	.0310	57.0
1557								

Table A.6.9. Final steady state conditions of on-line operations for Cases 8.1 and 9.1

	T _i °C	T °C	Δ _T _c	litre min	F _C litre min	C mol litre	(aKC)	Variac VR
Case 8.1								
(I) K ₁	= K ₂ =	4						
UOC	20.5	30.50	11.1	3.3	1.74	.1162	.0300	56.4
OMRAC	2							
K ₂ =200	21.0	31.70	13.1	3.3	1.48	.1016	.0310	57.0
(II) K ₁	= K ₂ =	15						
noc	21.0	31.50	12.8	3.3	1.54	.1046	.0310	57.0
OMRAC								
K ₃ =200	21.0	31.60	13.2	3.3	1.46	.1030	.0310	57.0
Case 9.1								
(I) C _d	= 0.10	g.mole/	litre					
noc	21.0	30.70	11.7	3.3	1.64	.1150	.0300	57.0
OMRAC								
K ₃ =200	21.0	31.50	12.5	3.3	1.58	.1030	.0310	57.0
(II) $C_s = 0.08$ g.mole/litre								
UOC	21.0	31.05	12.1	3.3	1.52	.1090	.0300	57.0
OMRAC								
K ₃ =200	21.0	31.75	13.6	3.3	1.42	.0990	.0310	57.0

Table A.6.10. Final steady state conditions of on-line operations for Cases 10.1, 10.2 and 10.3

	T _i	T	ΔT _c	F	Fc	C	(aKC) V	ariac
	°C	°c	°c_	litre min	litre min	mol litre	mu	VR
Case 10.1 C _o = 0.9 mol /litre								
US	20.5	30.80	11.6	3.3	1.40	.1030	.0280	54.4
UOC	20.5	31.00	12.7	3.3	1.30	.1006	.0290	56.0
OMRAC								
K ₃ =200	20.5	31.60	13.6	3.3	1.10	.0912	.0290	56.0
Case 10.2.	C _o =	1.1 mg	ol /lit	re				
US	19.5	28.90	6.8	3.3	4.10	.1480	.0330	59.5
UOC	19.5	30.70	8.3	3.3	2.80	.1260	.0340	60.0
OMRAC								
K ₃ =200	19.5	31.50	9.7	3.3	2.16	.1148	.0340	60.0
Case 10.3								
(I) C _o =	0.9 ,1	nol /lit	re					
UOC	19.5	31.20	13.2	3.3	1.16	.0980	.0280	54.3
OMRAC								
K ₃ =200	19.5	31.50	13.0	3.3	1.14	.0930	.0280	54 .3
(II) C _o =				2.02	o 50	1208	0340	60.0
	19.5	30.30	9.8	5.5	2.70	• 1290	•0)+0	00.0
OMRAC					2 12	/	07/10	60.0
K ₃ =200	19.5	31.60	10.1	3.3	2.40	.1116	.0540	00.0

APPENDIX 7

Optimal adaptivity calculation

- A.7.1. Optimal adaptivity of complete simulation
 Tables A.7.1 to A.7.5.
- A.7.2. Performance response calculation from dynamic response figures of on-line operation
- A.7.3. Optimal adaptivity of on-line operation Tables A.76 to A.718.

Table A.7.1. Optimal adaptivity of complete simulation for Cases 1.1, 1.2, 1.3 and 1.4

Case	Type of curves	$\int_{0}^{t} f_{e^{2}dt}$	Optimal adaptivity Ψ %	Figure
1.1	UOC	16.50		7.7
	OMRAC		•	
	K ₃ =100	7.10	57.00	7.7
	K ₃ =200	3.60	78.20	7.7
	K ₃ =500	1.70	89.70	7.7
	K ₃ =1000	0.85	94.84	7.7
1.2	UOC	65.00		7.10
	OMRAC			
	K ₃ =100	29.00	55.40	7.10
	K ₃ =200	15.50	76.15	7.10
	K ₃ =500	6.80	89.54	7.10
	K ₃ =1000	3.20	95.07	7.10
1.3	UOC	121.00		7.12
	OMRAC			
	K ₃ =100	69.00	43.00	7.12
	K ₃ =200	38.00	68.60	7.12
	K ₃ =500	17.00	86.00	7.12
	K ₃ =1000	10.00	91.73	7.12
1.4	UOC	178.00		7.14
	OMRAC			
	K ₃ =100	123.00	31.00	7.14
	K ₃ =200	66.00	63.00	7.14
	K ₃ =500	30.00	83.14	7.14
	K ₃ =1000	20.00	88.77	7.14

Table A.7.2. Optimal adaptivity of complete simulation for Cases 2.1, 2.2, 3.1, 3.2 and 3.3

Case	Type of curves	$\int_{0}^{t_{\mathrm{f}}} \mathrm{e}^{2} \mathrm{d}t$	Optimal adaptivity Ψ %	Figure
2.1	UOC	10.40		7.16
	OMRAC			
	K ₃ =100	5.60	46.15	7.16
	K ₃ =200	3.20	69.23	7.16
	K ₃ =500	1.60	84.61	7.16
	K ₃ =1000	0.80	92.50	7.16
2.2	UOC	35.50		7.19
	OMRAC			
	K ₃ =100	21.20	44.93	7.19
	K ₃ =200	12.50	67.53	7.19
	K ₃ =500	5.50	85.71	7.19
	K ₃ =1000	3.00	92.20	7.19
3.1	UOC	0.55		7.21
	OMRAC			
	K ₃ =100	0.41	25.45	7.21
	K ₃ =200	0.18	67.27	7.21
	K ₃ =500	0.04	92.72	7.21
	K ₃ =1000	0.015	97.27	7.21

Table A.7.2. (continued)

Case	Type of curves	o tf e dt	Optimal adaptivity \$\psi\$ %	Figure
3.2	UOC	3.10	£	7.22
	OMRAC			
	K ₃ =100	2.20	29.03	7.22
	K ₃ =200	1.30	58.06	7.22
	K ₃ =500	0.50	83.87	7.22
	K ₃ =1000	0.20	93.54	7.22
3.3	UOC	8.60		7.24
	OMRAC			
	K ₃ =100	5.90	31.39	7.24
	K ₃ =200	3.40	60.46	7.24
	K ₃ =500	1.40	83.72	7.24
	K ₃ =1000	0.70	91.86	7.24

Table 7.3. Optimal adaptivity of complete simulation for Cases 4.1, 5.1 and 5.2

Case	Type of curves	o e2dt	Optimal adaptivity ψ %	Figure
4.1	UOC	18.0		7.26
	OMRAC			
	K ₃ =100	9.8	45.55	7.26
	K ₃ =200	5.6	68.88	7.26
	K ₃ =500	2.4	86.66	7.26
	K ₃ =1000	1.3	92.77	7.26
5.1	UOC	18.2	a.	7.29
	OMRAC			
	K ₃ =100			
	= 0	9.•8	46.15	7.29
	= 1.0	6.2	65.93	7.29
	= 2.0	4.1	77.47	7.29
	= 3.0	3.2	82.41	7.29
	= 4.0	2.2	87.91	7.29
5.2	UOC	17.8	*:	7.31
	OMRAC	960:		
	K ₃ =200			
	= 0 `	5.6	68.53	7.31
¥2	= 2.0	3.2	82.02	7.31
	= 4.0	2.1	88.20	7.31
	= 8.0	1.1	93.82	7.31
	= 15.0	0.6	96.62	7.31

Table 7.4. Optimal adaptivity of complete simulation for Cases 6.1, 6.2, 7.1, 7.2 and 7.3.

Case	Type of curves	$\int_{0}^{t_{\mathrm{f}}} \mathrm{e}^{2} \mathrm{d}t$	Optimal Adaptivity $\psi~\%$	Figure
6.1	noc	17.0		7.34
	OMRAC, K ₃ =	1		
	€ = 0.5	10.2	40.00	7.34
	6 = 1.0	4.0	76.47	7.34
	£ = 1.5	2.0	88.23	7.34
	E = 2.0	1.2	92.94	7.34
6.2	noc	17.0		7.35
4	OMRAC, K ₃ =	3		
	£ = 0.5	8.50	50.00	7.35
	6 = 1.0	3.30	80.58	7.35
	6 = 1.5	1.70	90.00	7.35
	6 = 2.0	1.00	94.11	7.35
7.1	UOC	20.80		7.38
	OMRAC			
	K ₃ =100	11.60	44.23	7.38
	K ₃ =200	6.80	67.30	7.38
	K ₃ =500	2.80	86.53	7.38
	K ₃ =1000	1.50	92.78	7.38

Table 7.4. (continued)

Case	Type of curves	∫o tfe²dt	Optimal adaptivity Ψ %	Figure
7.2	noc	22,20		7.41
	OMRAC			
	K ₃ =100	12,60	43.24	7.41
	K ₃ =200	7.20	67.56	7.41
	K ₃ =500	3.20	85.58	7.41
	K ₃ =1000	1.80	91.89	7.41
7.3.	UOC	14.60		7.44
	OMRAC			
	K ₃ =100	8.20	43.83	7.44
	K ₃ =200	4.60	68.49	7.44
	K ₃ =500	1.90	86.98	7.44
	K ₃ =1000	1.00	93.15	7.44

Table A.7.5. Optimal adaptivity of complete simulation for Cases 8.1, 9.1, 10.1 and 10.2

Case	Type of curves	o e 2 dt	Optimal Adaptivity Ψ %	Figure
8.1	UOC	28.0		7.46
	OMRAC	2		*
	K1=K2=4	5.6	80.00	7.46
	UOC	19.6		7.46
	OMRAC			
	$K_1 = K_2 = 8$	5.6	71.42	7.46
	noc	11.6		7.46
	OMRAC			
	K ₁ =K ₂ =15	5.6	49.09	7.46
9.1	(I) UOC	13.6		7.48
	OMRAC	4.8	64.70	7.48
	(II) UOC	18.3		7.48
	OMRAC	6.2	66.12	7.48
	(Original valu	e ψ = 68.88	3%)	
10.1	(I) UOC	16.4		7.51
	OMRAC	5.4	67.07	7.51
	(II) UOC	23.6		7.51
	OMRAC	7.6	67•79	7.51
	(Original valu	ιe Ψ = 68.88	3%)	

Table A.7.5. (Continued)

Case	Type of curves	$\int_{0}^{t_{f}} e^{2} dt$	Optimal Adaptivity $\psi~\%$	Figure
10.2	(I) UOC	1.72		7.53
	OMRAC	0.72	58.13	7.53
	(II) UOC	54.00		7.53
	OMRAC	17.00	68.51	7.53

A.7.2. Performance response calculation from dynamic response figures of on-line operation

From Figure A.6.1 performance response is calculated as follows:

$$\int_{0}^{t_{f}} e^{2} dt = e_{1}^{2} \Delta t_{1} + e_{2}^{2} \Delta t_{2} + - - - e_{n}^{2} \Delta t_{n}$$
 (A-6-1)

Set:
$$\Delta t_1 = \Delta t_2 = - - - - - t_n = \Delta t$$
 (A-6-2)

and:
$$e_1 = \frac{A_1}{\Delta t_1} = \frac{A_1}{\Delta t}$$
, $e_2 = \frac{A_2}{\Delta t}$, $---e_n = \frac{A_n}{\Delta t}$ (A-6-3)

...
$$\int_{0}^{t_{f}} e^{2} dt = \frac{A_{1}^{2} + A_{2}^{2} + - - - + A_{n}^{2}}{\Delta t}$$

$$\stackrel{\text{n}}{\sim} \frac{\text{A}_{i}^{2}}{\Delta t} \tag{A-6-4}$$

In on-line plotting curves:

$$t_f = 600 \text{ sec}$$
 $n = 12$
 $t = 50 \text{ sec} = 1 \text{ in} = 2.54 \text{ cm}$
 $A = (0.1 \times 50) \left(\frac{\text{mol}}{1 \text{ itre}}\right) \text{ (sec)}$
 $t = 1 \text{ in}^2 = (2.54)^2 \text{ cm}^2$

 A_i can be obtained by using planimeter in $(cm)^2$, and equation A-6-4 then becomes:

$$\int_{0}^{t_{f}} e^{2} dt = \frac{1}{(2.54)^{4}} \sum_{i=1}^{12} A_{i}^{2} \left(\frac{in^{4}}{in} \right) = \frac{(0.1 \times 50)^{2}}{(2.54)^{4}(50)} \sum_{i=1}^{12} A_{i}^{2}$$

or
$$\int_0^{t_f} e^2 dt = 0.012$$
 $\sum_{i=1}^{12} A_i^2 \left(\frac{g \cdot mole}{L}\right)^2$ (sec) (A-6-6)

- 468 -

Performance response (PR) = \interester^2 dt

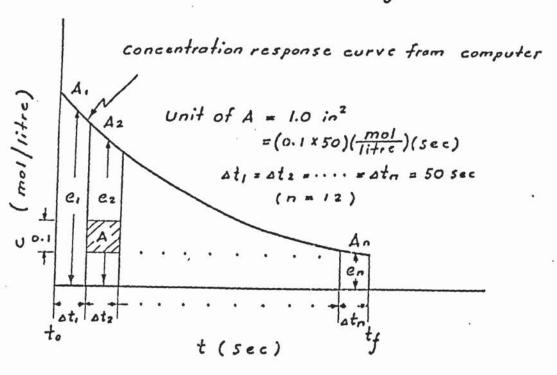


Figure A 7.1 Performance response

colculation from dynamic

response curve

Table A 7.6 Optimal adaptivity of On-line Operation for cases 1.1 and 1.2

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.0121A;	>~ >-
*								٠			* * * * .		:	
Case 1.1	(Figure 10.1)	10.1)												
0 0 U	5.75	8.95	7.50	5.40	4.10	3.55	3.55	3.60	3.60 3.60 3.65	3.65	3.65	3.65	3.68	
OMRAC					Ħ									
$K_{\chi} = 100$	4.90	6.75	3.75	1.00	0.65	0.89	1.20	1.40	1.50	1.60	1.80	1.60	1.20	67.39
$K_3 = 200$	4.5	6.20	2.90	09.0	0.50	0.70	1.20	1.20	1.40	1.50	1.60	1.40	96.0	73.91
$K_3 = 500$	4.00	3.50	0.70	0.85	0.40	0.55	0.80	06.0	1.10	0.80	08.0	09.0	0.41	88.86
$K_3 = 1000$	4.00	2.75	0.50	0.35	0.20	0.40	0.50	09.0	0.65	0.70	0.40	0.10	0.31	91.58
Case 1.2	(Figure 10.4)	10.4)												
0 0 U	7.60	7.60 14.0	11.25	7.45	4.95	3.70	3.70 3.15	2.75	2.75 2.75 2.60	2.60	2.5	2.5	6.22	
OMRAC												ĸ		
$K_z = 100$. 7.50	13.05	8.15	3.50	1.50	1.15	1.20	1.25	1.40	1.35	1.40	1.25	3.83	38.42
$K_{\xi} = 200$	7.20	10.30	4.65	1.25	.80	.95	1.10	1.25	1.20	1.20	1.00	1.10	2.49	63.18
$K_3 = 500$	6.75	6.30	.70	.55	.75	06.	1.00	.85	1.20	1.20	1.00	1.10	1.13	81.83
$K_3 = 1000$	6.30	4.80	.70	•30	.30	1.10	1.00	.85	.90	06.	.70	. 80	0.83	99.98
i.										94	9	•		

Table A 7.7 Optimal Adaptivity of On-line Operation for cases 1.3 and 1.4

					1								2	
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	$.012\Sigma A_1^2$	> -
Case 1.3	(Figure 10.6)	(9.0)												
D O U	4.80	4.80 10.80 12.65 12.10 11.10	12.65	12.10	_	10.15	9.75	08.6	9.56	9.65	9.75	9.45	14.76	
OMRAC														
$K_2 = 100$	4.60	7.45	7.05	5.85	5.40	5.20	5.40	5.40	5.50	5.50	5.56	5.50	4.76	67.75
$K_z = 200$	4.60	6.75	5.10	4.00	4.05	4.00	4.20	4.05	4.05	4.10	4.05	4.15	2.90	80.35
$K_{3} = 500$	4.60	5.75	2.80	1.65	2.15	2.35	2.25	2.25	2.25	2.25	2.15	2.15	1.25	91.53
$K_{\xi} = 1000$	4.40	4.90	1.70	1.25	1.95	1.70	1.70	1.40	1.55	1.50	1.70	1.45	0.83	94.38
$K_3 = 4000$	3.65	1.25	1.20	1.30	0.30	0.75	0.70	0.30	0.20	0.30	0.10	0	0.23	98.44
Case 1.4	(Figure 10.9)	(6.0)												
0 0 U	10.00	10.00 19.20	21.85	22.80 22.90	22	22.95	22.85	22.95 22.85 22.65 22.70 22.15	22.70	22.15	22.30	22.15	66.55	
OMRAC														
$K_z = 100$	10.00	17.95	17.25	14.60	13.15	12.65	12.45	12.65 12.45 12.60 12.65 12.60	12.65	12.60	12.45	12.40	26.49	60.20
$K_z = 200$	09.6	13.60	9.95	7.25	6.85	7.15	7.50	7.70	8.00	7.80	7.85	7.8	10.67	83.97
$K_{3} = 500$	9.55	10.00	4.75	3.56	4.85	5.45	5.45	5.30	5.10	5.10	5.05	2.00	5.28	92.07
$K_{\chi} = 1000$	9.40	6.35	0.95	2.85	4.20	3.90	3.56	3.65	3.85	3.80	3.45	3.5	3.00	95.49
,														

Table A 7.8 Optimal Adaptivity of On-line Operation for cases 2.1 and 2.2

•	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.012ZAį	→
Case 2.1	(Figure 10.11)	10.11)							i i	,				
0 0 U	1.85	6.85	8.45	8.50	9.20	9.10	8.05	8.60	8.45	8.25	8.15	7.75	9.38	
OMRAC														
$K_z = 100$	1.05	6.05	08.9	7.00	6.95	6.85	6.80	6.45	6.40	6.30	6.20	01.9	2.67	39.55
$K_z = 200$	1.50	5.45	5.40	5.15	5.00	4.80	4.60	4.35	4.35	4.30	4.10	4.05	2.96	68.44
$K_{z} = 500$	1.50	5.50	4.25	3.70	3.45		3.35	3.10	3.25	3.05	3.05	3.15	1.71	81.77
$K_3 = 1000$	1.80	4.05	3.15	2.80	2.80	2.55	2.55	2.50	2.50	2.40	2.40	2.40	1.06	88.70
Case 2.2	(Figure 10.14)	10.14)	2							-				
0 O U	4.55	4.55 10.55	12.55	13.40	13.75	14.00	13.85 14.10 14.20 14.95	14.10	14.20	14.95	14.15	13.90	24.76	
OMRAC														
$K_z = 100$	4.25	9.85	11.50	11.45	11.35	11.35	11.10 10.75 10.85	10.75		10.90	10.45	10.40	15.94	35.62
$K_{\chi} = 200$	4.25	9.50	9.75	8.75	8.50	8.45	8.20	8.25	8.00	7.78	7.00	7.35	9.44	61.87
$K_{2} = 500$	4.10	9.30	8.00	6.55	00.9	00.9	6.15	6.20	00.9	6.15	2.80	6.05	6.03	75.65
$K_3 = 1000$	2.70	6.15	3.80	3.20	3.70	3.90	3.95	4.00	4.25	4.10	4.45	4.55	2.47	90.05
)					*:	**								

Table A 7.9 Optimal Adaptivity of On-line Operation for cases 2.3 and 3.1

	Contract Con		STATE OF THE STATE OF												
		A1	A2	A3	A4	A5	A6	A7	A8	49	A10	A11	A12	.012£A½	<i>∾</i> ∘
	Case 2.3	(Figure 10.16)	10.16)												
	0 C	3.10	3.10 7.20	8.05	7.95 8.00	8.00	7.60	7.55	7.25	7.05	06.9	06.9	06.9	7.36	
	OMRAC														
	$K_3 = 100$	3.20	3.20 7.85	7.60	6.85	09.9	6.20	6.15	5.75	5.90	5.30	5.25	5.20	5.35	27.31
	$K_3 = 200$	3.05	6.75	5.80	5.25	5.20	4.80	4.40	4.35	4.40	4.20	4.15	4.15	3.29	55.30
	$K_3 = 500$	3.00	5.40	3.00	2.15	2.25	2.20	2.25	2.35	2.30	2.35	2.55	2.35	1.14	84.51
	$K_3 = 1000$	3.00	5.15	2.30	1.45	1.95	2.00	1.80	1.80	1.80	1.85	1.85	1.85	0.85	88.45
_	Case 3.1	(Figure 10.18)	10.18)												
	n o c	3.25	3.25 2.10	2.25	3.45	3.80	4.70	5.85	6.15	6.50	6.55	06.9	09.9	3.80	
	OMRAC														
	$K_3 = 100$	3.10	3.10 1.65	2.00	3.25	3.75	4.30	4.30	4.75	4.95	5.05	5.05	4.90	2.40	36.84
	$K_3 = 200$	3.10	1.50	1.40	2.50	3.45	4.00	4.05	4.45	4.65	4.70	4.90	4.75	2.09	45.00
	$K_3 = 500$	2.85	1.50	1.75	2.00	1.55	1.55	1.85	2.30	2.60	2.70	2.65	2.70	0.71	81.32
	$K_3 = 1000$	2.50	1.15	1.65	1.20	1.00	1.25	1.65	1.75	1.80	1.75	1.80	1.75	0.39	89.74
								100							12

Table A 7.10 Optimal Adaptivity of On-line Operation for cases 3.2 and 3.3

Case 3.2 (Figure 10.20) U O C		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.0122A ₁	→
4.55 3.00 1.65 4.75 6.90 8.15 8.65 8.75 9.25 10.00 11.15 12.60 9.47 3.85 1.55 2.65 5.00 6.20 6.70 6.85 6.95 7.25 8.05 9.20 10.65 6.52 3.85 1.55 2.25 3.95 4.85 4.85 4.70 5.00 5.70 6.80 7.75 3.51 3.45 1.75 2.60 2.30 2.35 2.40 3.20 3.35 3.80 4.45 5.55 6.20 2.23 3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.15 2.25 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	Case 3.2	(Figure	10.20)												
3.85 1.55 2.65 5.00 6.20 6.70 6.85 6.95 7.25 8.05 9.20 10.65 6.52 3.85 1.55 2.25 3.95 4.85 4.85 4.65 4.70 5.00 5.70 6.80 7.75 3.51 3.45 1.75 3.15 3.45 3.55 3.40 3.20 3.35 3.80 4.45 5.55 6.20 2.23 3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.55 6.20 2.23 2.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 5.30 1.45 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.45 2.00 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.05 12.75 13.85 9.44 2.45 1.20 3.55 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	0 C	4.55	3.00	1.65	4.75	06.9	8.15	8.65	8.75	9.25	10.00	11.15	12.60	9.47	
3.85 1.55 2.65 5.00 6.20 6.70 6.85 6.95 7.25 8.05 9.20 10.65 6.52 3.85 1.55 2.25 3.95 4.85 4.85 4.65 4.70 5.00 6.80 7.75 3.51 3.45 1.75 2.60 2.30 2.35 3.40 3.20 3.35 3.80 4.45 5.55 6.20 2.23 2.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.55 6.20 2.23 2.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.35 1.45 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.05 12.75 13.85 9.44 2.40 1.20 3.55 6.30 2.55 2.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.35 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.20 1.80 2.40 2.95 3.05 2.85 0.55 11.85 0.80 0.75 0.95 0.75 1.20 2.75 2.90 2.55 2.15 2.25 4.05 2.35 2.35 2.35 2.35 2.35 2.35 2.35 2.3	OMRAC														
3.85 1.55 2.25 3.95 4.85 4.65 4.70 5.00 5.70 6.80 7.75 3.51 3.54 3.45 1.75 3.15 3.45 3.55 3.40 3.20 3.35 3.80 4.45 5.55 6.20 2.23 3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.35 6.20 2.23 2.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.05 12.75 13.85 9.44 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.55 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_3 = 100$	3.85	1.55	2.65	5.00	6.20	6.70	6.85	6.95	7.25	8.05	9.20	10.65	6.52	31.15
3.45 1.75 3.15 3.45 3.55 3.40 3.20 3.35 3.80 4.45 5.55 6.20 2.23 3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 1.45 2.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.05 12.75 13.85 9.44 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_3 = 200$	3.85	1.55	2.25	3.95	4.85	4.85	4.65	4.70	5.00	5.70	6.80	7.75	3.51	62.94
3.45 1.75 2.60 2.30 2.35 2.40 2.45 2.80 3.00 3.45 4.45 5.30 1.45 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.65 1.45 2.90 5.10 6.50 6.40 6.65 7.55 9.05 11.05 12.75 13.85 9.44 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_3 = 500$	3.45	1.75	3.15	3.45	3.55	3.40	3.20	3,35	3.80	4.45	5.55	6.20	2.23	76.45
Figure 10.22 and 10.25) 2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.65 1.45 2.90 5.10 6.50 6.40 6.65 7.55 9.05 11.05 12.75 13.85 9.44 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.85 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_3 = 1000$	3.45	1.75	2.60	2.30	2.35	2.40	2.45	2.80	3.00	3.45	4.45	5.30	1.45	84.69
2.45 1.20 3.85 6.75 8.35 8.95 9.55 10.40 12.25 14.45 16.60 18.05 16.53 2.65 1.45 2.90 5.10 6.50 6.40 6.65 7.55 9.05 11.05 12.75 13.85 9.44 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.55 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	, Case 3.3	(Figure		and 10.	25)										
2.65 1.45 2.90 5.10 6.50 6.40 6.65 7.55 9.05 11.05 12.75 13.85 9.44 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	0 0 D	2.45	1.20	3.85	6.75	8.35	8.95	9.55		12.25	14.45	16.60	18.05	16.53	
2.65 1.45 2.90 5.10 6.50 6.40 6.65 7.55 9.05 11.05 12.75 13.85 9.44 2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	OMRAC														
2.45 1.20 3.55 5.35 6.00 5.95 6.15 6.75 8.10 9.95 11.45 12.10 7.75 2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_{\chi} = 100$	2.65	1.45	2.90	5.10	6.50	6.40	6.65	7.55	9.05	11.05	12.75	13.85	9.44	42.89
2.00 1.20 3.50 4.50 4.65 4.35 4.35 5.15 6.35 7.75 8.85 8.80 4.56 2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_3 = 200$	2.45	1.20	3.55	5.35	00.9	5.95	6.15	6.75	8.10	9.95	11.45	12.10	7.75	53.12
2.00 1.20 2.75 2.90 2.55 2.15 2.25 4.05 5.35 5.95 6.10 1.99 1.85 0.80 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_{\chi} = 500$	2.00	1.20	3.50	4.50	4.65	4.35	4.35	5.15	6.35	7.75	8.85	8.80	4.56	72.41
1.85 0.80 0.75 0.75 0.95 0.85 1.25 1.80 2.40 2.95 3.05 2.85 0.52	$K_{\chi} = 1000$	2.00	1.20	2.75	2.90	2.55	2.15	2.25	2.25	4.05	5.35	5.95	6.10	1.99	87.96
	$K_3 = 4000$	1.85	0.80	0.75	0.75	0.95	0.85	1.25	1.80	2.40	2.95	3.05	2.85	0.52	96.85
	00000														

Table A 7.11 Optimal Adaptivity of On-line Operation for cases 4.1 and 4.2

2		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.0122A ₁	→
5	Case 4.1	(Figure 10.27)	10.27)												
	0 C	0.20	3.50	5.00	5.50	5.90	6.35	6.9	7.25	7.50	7.50	7.95	8.05	5.80	
	OMRAC														
	$K_z = 100$	0.20	2.60	3.95	4.10	4.00	4.35	4.70	5.00	5.20	5.25	5.60	5.75	2.88	50.34
	$K_{\zeta} = 200$	0.10	2.50	3.35	3.05	3.35	3.85	4.30	4.65	4.85	4.85	5.00	5.00	2.27	98.09
	$K_{\chi} = 500$	0.10	2.40	2.80	2.55	2.95	3.55	3.70	3.90	4.05	4.10	4.00	4.00	1.47	74.66
	$K_{z} = 1000$	0.0	2.25	1.90	1.25	1.80	2.15	2.35	2.65	2.70	2.70	2.70	2.70	0.72	87.59
	$K_3 = 4000$	0.0	1.65	0.50	1.15	1.25	1.35	1.40	1.40	1.50	1.45	1.25	1.45	0.24	92.86
	Case 4.2	(Figure 10.29)	10.29)												
	0 O	1.05	4.65	7.45	9.20	10.35	11.45	11.45 12.25 12.95 13.40 13.70	12.95	13.40	13.70	13.90	14.10	17.74	
	OMRAC														
	$K_z = 100$	0.40	4.05	6.55	7.55	8.20	9.20	9.65	9.85	10.35	10.40	10.15	10.40	10.01	40.19
	$K_{\chi} = 200$	0.40	4.05	6.15	6.80	7.10	7.55	7.95	8.15	8.25	8.05	7.90	7.95	7.15	59.70
	$K_{\chi} = 500$	0.20	3.65	4.60	4.30	4.30	4.75	5.05	5.15	5.25	5.30	5.20	5.25	3.08	82.64
	$K_{\chi} = 1000$	0.20	3.30	3.00	2.65	2.80	2.65	2.90	3.10	3.25	3.20	3.30	3.35	1.23	93.07
	$K_3 = 4000$	0.20	2.55	1.60	2.05	2.30	2.30	2.55	2.55	2.60	2.45	2.40	2.45	0.74	95.83
)														

Table A 7.12 Optimal Adaptivity of On-line Operation for cases 5.1 and 5.2

								AND DESCRIPTION OF THE PERSON		The second state of the second					
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.0122A1	% →
	*Case 5.1	(Figure 10.32)	10.32)												
	OMRAC														
	$K_{\chi} = 100$					8			ı	Si.					
	(=0.0	0.40	3.95	6.95	7.25	6.10	8.25	8.75	9.05	9.25	09.6	10.00	10.20	9.15	48.42
	6 =1.0	0.40	4.60	5.00	3.60	5.80	2.60	1.90	1.25	1.00	0.80	0.75	0.90	1.29	92.73
	£ =2.0	0.30	3.30	3.50	1.10	4.95	0.65	1.40	09.0	0.85	1.95	2.60	2.55	0.83	95.32
	6 = 3.0	0.30	2.95	2.00	09.0	3.80	1.65	0.80	0.90	2.70	3.25	2.50	1.10	89.0	96.17
	*Case 5.2	(Figure	(Figure 10.34)	ā)	. **	ď									**
47	OMRAC														
6 -	$K_3 = 100$														
	0.0= 3	0.35	3.80	6.35	7.05	7.55	8.50	9.25	9.55	9.70	9.70	9.62	9.65	9.42	46.90
	6 =0.2	0.25	3.40	6.10	09.9	6.65	6.95	7.25	6.95	6.75	6.45	5.90	5.70	5.28	70.24
	6 =0.4	0.20	3.10	5.80	09.9	6.35	6.05	5.45	4.95	4.35	3.60	3.10	2.40	3.18	82.07
	9 * 0 = 3	0.10	3.10	5.80	2.15	00.9	5.15	4.45	3.95	3.45	2.75	2.25	1.25	2.06	88.39
	6 =0.8	0.0	2.90	4.30	2.60	4.95	4.20	3.35	2.65	2.15	1.55	1.20	1.05	1.54	91.32
	(=1.0	0.0	2.90	4.30	5.40	4.45	3.30	2.15	1.45	1.05	0.65	0.65	0.70	1.15	93.52
									115 - 12 - 12 - 12 - 12 - 12 - 12 - 12 -						
										50		2017 DOM: 14			

* Refer to Case 4.2 U 0 C 0.012 $\Sigma A_1^2 = 17.74$

Table A 7.13 Optimal Adaptivity of On-line Operation for cases 5.3 and 6.1

						i.	ė.	•							
		A1	A2	A3	A4	A5	A6	A7	A8	A9.	A10	A11	A12	.0122A ₁	- }-
	*Case 5.3	(Figure	(Figure 10.37)												
	OMRAC				Š					£.					
	$K_z = 200$														
	6 =0.0	0.30	3.25	5.10	5.65	6.20	6.70	7.15 · 7.65	7.65	7.60	7.75	7.65	7.75	2.98	66.29
	(=0.2	0.20	3.05	4.80	4.95	5.10	5.40	5.70	5.95	5.85	2.90	5.85	5.45	3.75	78.86
	t =0.4	0.20	2.80	4.80	4.70	4.45	4.20	4.30	4.45	4.35	4.30	3.85	3.45	2.31	86.98
	9.0= 3	0.20	2.80	4.40	4.25	4.45	3.90	3.80	3.75	3.40	3.20	2.85	2.15	1.72	90.30
	6 =0.8	0.10	2.45	4.40	4.25	3.95	3.90	3.80	3.40	3.10	2.70	2.45	2.00	1.53	91.38
- 4	6 =1.0	0.10	2.30	3.95	3.75	3.10	2.60	2.35	2.30	2.25	2.00	1.75	1.45	0.92	94.81
77	Case 6.1	(Figure	10.39)	_											
-	0 0 U	0.45	3.25	6.70	6.85	9.25	10.25	10.25 11.25 12.00	12.00	12.40 12.50	12.50	12.55	12.55	14.44	
	OMRAC											•			
	$K_z = 1.0$														
	(=0.1	0.40	3.15	6.20	8.65	9.65	06.6	9.55	8.70	7.65	6.50	5.20	3.70	7.47	48.27
	€ =0.2	0.30	2.85	5.40	6.40	6.65	5.75	4.45	3.00	1.35	0.50	1.30	2.25	2.32	83.93
	£ =0.3	0.20	2.85	5.05	5.85	5.7	4.5	2.25	0.85	.85	1.95	2.55	2.40	1.74	87.95
	6 =0.4	0.20	2.85	5.05	5.35	4.40	2.65	0.65	1.70	2.85	3.25	2.85	1.45	1.45	96.68
							,								

 $U \circ C \circ 0.012 \Sigma A_{1}^{2} = 17.74$ Refer to Case 4.2

Table A 7.14 Optimal Adaptivity of On-line Operation for Cases 6.2 and 6.3

		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	$.012\Sigma A_{1}^{2}$	% →-
	Case 6.3	(Figure 10.43)	10.43)												
	0 0 U	0.50	0.50 4.20	6.55	7.55	8.60	9.35	10.2	11.0	11.0 11.70 12.15	12.15	12.45	12.65	13.24	
	OMRAC														
-	$K_z = 10$														
	£ =0.0	0.20	3.05	4.45	5.05	5.75	6.50	7.30	7.95	8.35	00.6	9.30	9.62	6.92	47.73
	£ =0.04	0.20	2.90	3.95	4.65	5.20	5.75	6.10	6.50	6.40	6.45	6.50	6.40	4.21	68.20
	e =0.08	0.10	2.90	3.95	4.65	5.10	4.95	4.80	5.95	5.10	4.75	4.60	4.70	2.96	77.64
	£ =0.12	0.10	2.75	3.50	3.90	4.15	4.30	4.20	4.55	4.50	4.25	3.55	2.75	2.01	84.82
- 1	Case 6.3	(Figure	10.48)												
78	0 O U	0.90	2.90	6.25	7.95	8.95	08.6	10.35	11.0	11.0 11.6	11.8	12.20	12.55	13.15	
_	OMRAC														
	$K_z = 20$					*									
	0.0= 3	1.00	1.20	1.65	2.00	2.60	3.25	3.90	4.55	4.95	5.35	5.45	2.60	2.12	83.88
	£ =0.04	1.00	1.05	1.25	1.65	1.90	2.35	2.80	3.25	3.50	3.60	3.75	3.75	1.05	92.02
	£ =0.08	1.20	1.00	1.20	1.40	1.60	1.90	2.10	2.40	2.60	2.80	3.10	3.15	0.67	94.90
	£ =0.12	1.10	8.0	0.95	1.15	1.60	1.80	1.95	2.05	2.20	2.25	2.10	2.10	0.44	96.65

Table A 7.15 Optimal Adaptivity of On-line Operation for cases 7.1 and 7.2

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.0122A1	» >-
Case 7.1	(Figure 10.50)	10.50												
0 0 n	4.40	68.9	7.70	9.05	10.65	12.65	14.65	15.95	17.00	10.65 12.65 14.65 15.95 17.00 17.80	18.55	19.00	27.14	
OMRAC														
$K_z = 100$	4.15	6.05	7.05	8.45	10.00 11.	11.45	12.60	13.75	14.35	45 12.60 13.75 14.35 14.75 15.00	15.00	15.60	19.75	27.23
$K_z = 200$	3.20	5.05	6.10	7.25	8.30	9.56	56 10.6 11.05 11.50 11.65	11.05	11.50	11.65	11.95	12.05	12.91	52.43
$K_{\chi} = 500$	3.20	4.45	4.85	5.10	5.80	6.50	50 7.10 7.60 7.75	7.60		8.15	8.40	8.50	6.40	76.42
$K_3 = 1000$	3.20	41.50	3.80	3.60	4.20	4.80	5.10	5.55	5.85	5.90	6.10	6.35	3.59	86.77
Case 7.2	(Figure 10.53)	10.53)	_											
2 0 n	3.55	8.70	8.70 11.00	11.65	11.80	12.75	11.80 12.75 13.35 14.1	14.1	14.45 14.9	14.9	14.85	14.95	22.79	
64 OMRAC														
$K_{\chi} = 100$	3.56	7.90	9.75	10.0	9.60 10.	10.15	15 10.40 11.05 11.30 11.25	11.05	11.30	11.25	11.35	11.45	14.52	36.29
$K_z = 200$	3.45	7.75	9.15	8.65	8.35	8.45	8.50	8.55	8.60	8.75	8.80	8.95	06.6	26.56
$K_z = 500$	2.95	6.75	6.50	5.05	4.90	4.80	4.90	5.05	5.15	5.15	5.15	5.55	3.95	82.67
$K_3 = 1000$	2.40	5.30	4.90	4.00	3.15	3.10	3.15	3.60	3.60	3.00	2.95	3.95	1.95	91.44

Table A 7.16 Optimal Adaptivity of On-line Operation for Cases 7.3 and 8.1

			4.5												
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	.012ΣA ₁	. ~
	Case 7.3		(Figure 10.56)	6)											
	O 0	0.80	3.45	6.80	9.30	11.05	11.85	12.55	12.95 13.00 13.10	13.00		13.40	13.55	17.21	
	OMRAC														
	$K_z = 100$	0.70	1.55	3.75	6.05	7.20	7.60	7.85	8.30	8.30	8.25	8.20	8.25	6.19	60.55
	$K_z = 200$	0.40	2.15	3.60	5.05	6.10	6.25	5.75	5.30	5.15	4.80	4.65	4.65	3.28	80.94
	$K_2 = 500$	0.40	1.20	2.65	4.50	4.35	4.95	5.00	4.90	4.35	4.30	4.20	3.85	2.29	86.69
	$K_3 = 1000$	0.40	0.90	1.85	3.25	3.05	3.00	3.15	3.30	3.25	3.25	3.30	3.40	1.17	93.20
- A	*Case 8.1		(Figure 10.59)	6											
8O =	$I \cdot K_1 = K_2 = 4$	14 0 75	7 7 7	7 05	α υ	10.	1.20	13.35	14.60	15.80	13.35 14.60 15.80 16.45	16.90	16.95	22.53	
	OMRAC		•			•									
	$K_3 = 200$	0.10	4.05	4.55	4.45	4.95	5.55	6.20	6.75	6.95	7.30	7.30	7.00	4.81	78.65
	II $K_1 = K_2 = 15$	=15													
	0 0 n	0.20	3.60	7.75	10.2	10.55	11.1	11.25	11.55	11.35	11.5	11.55	11.6	14.35	
	OMRAC														
	$K_3 = 200$	0.20	3.45	7.35	8.85	9.45	10.15		10.70	10.55	10.55 10.70 10.55 10.45	10.40	10.50	12.02	16.24
	*	Refer to case 4.2, K ₁ =K ₂ =8, K ₃ =200,	case	4.2, K ₁	=K ₂ =8,	K ₃ =200,	# }-	59.67\$							

Table A 7.17 Optimal Adaptivity of On-line Operation for cases 9.1 and 10.1

		A1	A2	A3	A4	A5 A6	A6	A.7	A8	A9	A10	A7 A8 A9 A10 A11 A12	A12	$.012\Sigma A_{1}^{2}$ ψ \$	÷
	*Case 9.1	(Figure	(Figure 10.61)												
	IUOC	0.30	0.30 4.15 7.25	7.25	10.4 11.7	11.7	9.25	12.75	13.40	13.85	14.45	9.25 12.75 13.40 13.85 14.45 14.55 14.25	14.25	18.70	
	OMRAC														
	$K_{\chi} = 200$	0.20	0.20 3.35 4.70	4.70	5.15	5.50	4.85	5.75	85 5.75 6.10 6.15 6.30	6.15		6.30	6.30	4.09	78.13
	II U O C	0.30	4.75	7.5	10.3	11.3	8.95	12.00	95 12.00 12.95 13.65 14.15	13.65	14.15	14.35	14.60	18.12	
	OMRAC									,					
-	$K_3 = 200$	0.45	0.45 4.80 6.2	6.2	6.3	6.35	6.10	6.75	10 6.75 7.00 7.40 7.80	7.40	7.80	7.85	7.80	6.14	66.1
481	*Case 10.1		(Figure 10.63)	3											
_	U 0 C	0.75	1.50	0.75 1.50 5.55	7.75	9.25 10.		11.60	12.55	13.00	13.25	50 11.60 12.55 13.00 13.25 13.35 13.50	13.50	15.44	
	OMRAC														
	$K_3 = 200$	0.75	1.75	0.75 1.75 5.30 5.95 6.10 6.45 6.90 7.30 7.50 7.75 7.50 7.65	5.95	6.10	6.45	06.9	7.30	7.50	7.75	7.50	7.65	5.73	62.8

* Refer to case 4.2 $K_3=200$ $\psi = 59.67$

Table A 7.18 Optimal Adaptivity of On-line Operation for cases 10.2 and 10.3

		A1	A2	A3	A4	A5	A6	A7	A8	A9	A9 A10	A11	A12	.012ΣA ²) -	6/0
-482-	* Case 10.2 (Figure 10.65) U O C 1.45 7.25 9 OMRAC K ₃ =200 1.15 6.6 8 *Case 10.3 (Figure 10.67) I U O C 3.25 3.65 1 OMRAC K ₃ =200 3.20 2.85 0 II U O C 4.05 10.9 14 OMRAC	2 (Fig 1.45 1.15 1.15 (Figu 3.25 3.25 4.05	(Figure 10.65) 1.45 7.25 9.95 1.15 6.6 8.25 (Figure 10.67) 3.25 3.65 1.05 3.20 2.85 0.35 4.05 10.9 14.50	65) 9.95 8.25 1.05 0.35 14.50	11.70 8.85 .55 0.75 17.60		14.95 10.30 2.70 1.15 21.15	13.60 14.95 16.15 17.20 17.75 18.25 9.50 10.30 10.65 10.95 11.35 11.60 1.70 2.70 3.45 4.15 4.55 4.80 1.15 1.15 1.45 1.70 2.05 2.00 19.65 21.15 22.50 23.40 24.2 24.55	17.20 10.95 4.15 1.70 23.40	17.75 18.25 11.35 11.60 4.55 4.80 2.05 2.00 24.2 24.55	18.25 11.60 4.80 24.55	3.60 14.95 16.15 17.20 17.75 18.25 18.75 18.90 9.50 10.30 10.65 10.95 11.35 11.60 11.65 11.75 1.70 2.70 3.45 4.15 4.55 4.80 5.00 4.95 1.15 1.15 1.45 1.70 2.05 2.00 2.15 1.95 9.65 21.15 22.50 23.40 24.2 24.55 24.70 25.4	18.90 11.75 4.95 1.95 25.4	31.35 13.90 1.89 0.52 59.83	55.66	
	$K_3 = 200$	3.25	3.25 9.45 11.1	11.1	11.55	11.55 11.85 12.	12.65	65 13.10 13.55	13.55	13.75	13.75 13.70 13.65		13.55	21.11	64.72	
		* Refer	to cas	* Refer to case 4.2 K_3 =200	K ₃ =200	ψ = 59.6	59.67\$									1

-482-

NOMENCLATURE

The nomenclature in use throughout the thesis is given in the following list. Special symbols which appear from place to place are defined where they occur.

English letter symbols

	*
A	Area
A	Constant in Arrhenius equation
A (I,J)	Matrix notation where I and J are the numbers of
	rows and columns respectively.
a	Catalyst activity (%)
a _i	Constants in parameter space and constraint limit
a ij	Linearised coefficients of process state variable 0 i.
a' _{ij}	Modified linearisation coefficients of process
	state variable 0 i.
B (I,J)	Matrix notation where I and J are the numbers of
	rows and columns respectively
B'	Constant in Liapunov function
b	Constant in constraint limit
b	Linearised coefficient of process control variable, m.
b'	Modified linearisation coefficient of process control
	variable, m.
C	Concentration of reactant in the reactor (mol/litre)
C.	Concentration of reactant in feed to reactor (mol/litre)
$^{\mathtt{C}}_{\mathtt{r}}$	Optimal model reference concentration (mol/litre)
c _d	Set-point concentration
c _p	Specific heat of reactant (cal/g C)
Cpc	Specific heat of cooling water (cal/g°C)
ci	Constants of equations (1-1) and (1-2)

```
D
           Derivative controlling action
D(i)
           Notation for linearisation coefficients where
                                                             1 10
           an integar
           Linearised coefficients of process load variables 0 Li
dij
           Modified linearisation coefficient of process load
d'
           variable 0 ..
           Activation energy, a constant (cal/mol)
E
           Response error
F
           Function
           Matrix of f,
F
           Inlet flowrate to the reactor (litre/min)
           Cooling water flowrate (litre/min)
           Signal of F after VDFG (volts)
           Signal of Fafter V/I converter (ma)
F<sub>V/I</sub>
           Signal of F_c after I/P transducer (psig)
F<sub>I/P</sub>
           Signal of F after valve positioner (psig)
Fp
F(J)
           Matrix notation where J are the column numbers
F(i)
           Notation of function equations
f
           Functional equation
f
           Function
fi
           Function of simultaneous algebraic equation
G
           Function
H
           Function
Η
           Hamiltonian Function
\DeltaH
           Change of enthalpy on reaction (cal/mol)
           Function
h
I
           Integral controlling action
I
           Current (ma)
```

Unit matrix

I

J	Performance index or objective function
J'	First derivative of J
J"	Second derivative of J
K	Velocity constant (sec-1)
K	Gain
K _c	Controller gain
K _v	Control valve gain
K	Weighting factors
L	Time constant (sec)
М	Maximum value of m
m	Control variable
m	Control variables of OMR scheme
m*	Optimal control law of OMR scheme
N	Integers
n	Integers
P	Proportional controlling action
P(i)	Notation of weighting factors
P _i	Parameters
P _i *	Constant normal parameters
Q _g	Rate of heat generation (Kcal x $10^3/h$)
Q _c	Rate of heat removal by water cooling coil
	(Kcal/min)
^२ ८*	Optimal rate of heat removal by water cooling
·	coil (Kcal/min)
9 _{gg}	Signal of Q after VDFG (volt)

Universal gas constant (cal/ mol oK) R Liapunov stability region R R(I) Matrix notation where I are the numbers of rows Performance index S Laplace transform complex variable s Temperature in the reactor (°C or °K) T Temperature of feed inlet to reactor (°C or °K) Inlet temperature of cooling water (°C or °K) Tcl Outlet temperature of cooling water (°C or °K) Time (sec) t Control variables of OAC scheme U* Modified optimal control law of OAC scheme Volumetric holdup in reactor (litres) V V Liapunov function V Voltage (volt) X Matrix of x ; $\overline{\mathbf{x}}$ Roots of matrix of f. Xi ith no. of iteration variables x, Z Steepest descent slope

Greek letter symbols

$\alpha_{i}, \beta_{i}, \gamma_{i}, \delta_{i}$ and ζ_{i}

Optimal control law coefficients

Optimal control law coefficients of the OMR scheme

Optimal control law coefficients of the OAC scheme

Time scaling factor

Weighting factor of optimal integral control £ i (X) A Change of variable **9** , Process state variables 0 _i* Optimal process state variables Optimal process state variable profiles as OMR Input signal of control system **9** d Setpoint of OMR scheme e Li Process load variables Constant λ Adjoint variables λi Product of variables II Density of process fluid (gm/cm³) P Density of cooling water (gm/cm³) Pc. Σ Summation τ Machine time of X-Y plotting (sec) Optimal PID control law Optimal adaptivity (%) Frequency w

Subscripts

f final
i integers
j integers
m maximum
s steady state
o initial

Abbreviations

Amplifier Amp CSTR Continuous stirred tank reactor HG High gain Inv Inverter MRAC Model reference adaptive control Optimal model reference OMR OAC Optimal adaptive control OMRAC Optimal model reference adaptive control Machine unit; 1 mu = 10 volt mu PI Performance index Performance response PR Potentiometer Pot Temperature recorder TR Temperature recording controller TRC US Unadapted system UOC Unadapted optimal control VR Variac reading (0-100) VDFG Variable diode function generator

Scaled computer variable (mu)

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