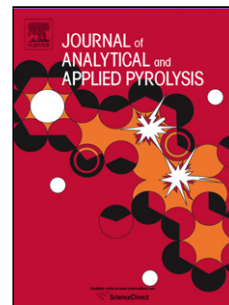


# Journal Pre-proof

A Predictive PBM-DEAM Model for Lignocellulosic Biomass Pyrolysis

Hongyu Zhu, Zhujun Dong, Xi Yu, Grace Cunningham, Janaki Umashanker, Xingguang Zhang, Anthony V. Bridgwater, Junmeng Cai



PII: S0165-2370(21)00217-5  
DOI: <https://doi.org/10.1016/j.jaap.2021.105231>  
Reference: JAAP 105231  
To appear in: *Journal of Analytical and Applied Pyrolysis*  
Received Date: 22 March 2021  
Revised Date: 30 May 2021  
Accepted Date: 4 June 2021

Please cite this article as: Zhu H, Dong Z, Yu X, Cunningham G, Umashanker J, Zhang X, Bridgwater AV, Cai J, A Predictive PBM-DEAM Model for Lignocellulosic Biomass Pyrolysis, *Journal of Analytical and Applied Pyrolysis* (2021), doi: <https://doi.org/10.1016/j.jaap.2021.105231>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier.

\$ 3HEM3%0 (00RHO RUQFHOOXORVE%RPDVV  
3ROVV

RE MRO L< X DHRP -DQNDENU QXDQ  
=KDQ, NRQ%DWU -XPHQL

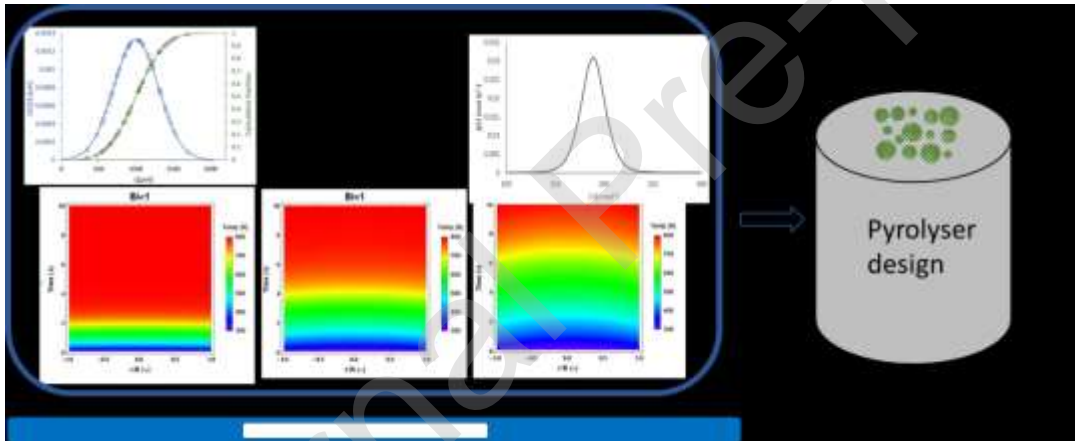
(HU%RSR&FW5HVHDEK, QMM(%5, ROOHJHR(QHIDGKVEDO6FHQHV \$RQ  
8NHVWQDQOH%PKDP %(78RQSP

%RPDVV(HI(QHIDHVHDEKMMH/DERDMR8EDQ \$EXOMH6RXKQMM  
\$EXOMH6FKRROR\$EXOMHDQRORJ6KDKDIDR7RQ8HVMQFKXD6RD6KDKDL  
3HRSOHY5HSXEOERKQ

HSDHFKHPVWFKRROR6FHEH8HVMKDKDR6FHQHD QHFKRORJXQDQ  
5RD6KDKDB5KQ

BHVSRIQXWRV X [XDVQFXN -XPHQL MPFD#MMWH6FQ

DSKEDEVMFV



+IKOIKW

3/4 0% ■

3/4 ■ ■ ■ ■

3/4 ■ ■ ■ ■ ■ ■ ■ ■

■

3/4 1 ■ ■ ■ ■ ■ ■ ■ ■

EVDFW

3ROVMSRPLM DQMMZ\ WRQW OLQHOORRELRPDV ORDERQ  
HPLRQHQRW V7RHIIHEMOMELRPDV IHHAN ZHGMERQ WSRN  
ELRINDRPSHKHM NQDPRHO RIMSREIV RQ DSDWQHOHMOILPSRW,Q  
W W SRSQDERQDODEPRHO3% GLEMG DEDRQHPRHO 0 RSOHG  
PRHOLMMPHHMORSHHSHGELRPDSROV N 3RSQDERQDODEPRHOLMW  
SHMW MUDEOMHGWERQ RIKOGRPSRMG IRP MLQLRPDV WSRMU 7E  
GIIHNSQDPRHOV DHHPEHGLQ W RQDWRHTNRQIPDMQHU KDH  
RPSDHQHPRQWWSHGERSHIREDERIEDM SXPHEHSHOVSREIV  
RIELRPDZRPEDOMHGWERQ ,WRQW QRLKRPDONQDZMMQW  
DSW LQ SDWQHPSHDW GWERQ WHLQWQWDEOHGIIHHERIKDM  
SXPHEHSHQHDQWMSDQHLH

.HRQ MEXMDFMDMHI PRHO\$03RSXODQDODEPRHO3%0  
HEV%RPDVVSROVM7HPSHDWHEXEQ

1RP HQODWH

EEHDERQ

&	RPSMRQOIOKPLF
0	LEMCEWRQHPRHO
30%	3RSQDERQDODEPRHO
0	RLMRQW
0	RODWOHPDWU
&	LHERQ
3f	3ODFDHDWGDPLQHQLHQORZDU
625	6LQHILWHHDERQ

5RPDQPEROV

\$	3H HSRQDQDQWUQMSHRQ
%	WRQHU
&S	HDSDEW
(	WRQHQU
+	SHDERQDW
K	HQONDQWHRHILEHQ
N	.LHERQW

N<sub>II</sub> (HFW KHPDOFRQFMM ERPDVV  
 / KDDFWFOHQW  
 1 MROPEHRWHYROXPHDSSRDFK  
 3 5HDFKQHDVEVREHGVROHPDQ  
 5 8QHMDOJDVFRQDW  
 U 3DEOHDEV  
 N6 RQHVRQW  
 7 7HPSHDWH  
 W 7PH  
 9 9ROXPH  
 ; 0DVVDFEQ

EHN VPEROV

! MNQW  
 é<sub>4</sub> ,QDDOHQWELRPDSVDWH  
 — HDMON  
 1 6MQHEDRQ  
 . RQVRQH  
 & 3RHHPLMW

6KESW

% LRPDV  
 F &RHRHWRPDSVDWH  
 HY HKODEOLDERSRHV  
 G URRHV  
 0 RLM  
 9 RODWH  
 & EU  
 S 3DWH  
 V 6DERHWRPDSVDWH  
 ,QDDOH

6XHSW

E ELRPDV

,QRQ

HSHOMVWRERPLDORRMRSHKK RQDDQPDHUDOMVOLTKG  
 KOLDQMV RE UQ LQDEMRIRHQ @ FLHOMKOLGLTK DQMV

SR&FRPSROV/ODIHOHSHQWHRSHD&FRQ @ HDF&ERIXD&Q @  
 D&KVERFKHPEDOSRSH&VVRERPDVV @ 7KHDV&ROV&MFKRORJ&ROIX&SR&FWKDV  
 EHHQ YHORSH&HFH&QDFHV @ ,&DS&R&FHKIKHOC&RDIX&HOXS&M&W  
 PR&D&RSHD&M&P&SHD&X&H&D&Q&K&R&V&H&H&H&V&O&H&V&V&K&D&Q @ )DV&ROV&M&F&K&R&O&R&J&  
 DOVRF&D&H&X&V&H&M&H&F&R&Y&H&H&Q&I&R&P&H&H&H&V&R&D&V&M&H&J&P&X&E&S&D&O&V&R&O&D&V&W @  
 V&H&D&J&H&V&O&X&H&@ R&D&V&O&X&H @ D&S&O&D&V&E&W @ 7KHDV&ROV&M&H&S&H&V&H&Q&W&H&D&S&K&H&D&Q XS  
 D&W&K&R&V&Y&D&S&R&X&M&H&E&H&H&D&V&R&R&O&I&R&Q&M&D&Q&I&K&E&L R&R&D&H&O&G&@ \$&W&H&O&E&X&G  
 S&R&F&W&K&D&Y&H&K&I&K&H&H&Q&H&Q&M&D&Q&R&O&R&E&L&D&V&K&H&O&V&D&M&H&D&H&D&V&M&E&H&D&Q&S&R&H&D&Q  
 X&V&H&M&H&D&V&ROV&M&R&E&R&P&D&V&V&F&X&H&O&D&M&F&W&H&D&M&M&H&H&O&R&H&Q&U @ 7KH  
 H&D&F&E&S&D&W R&I&M&H&E&R&P&D&V&S&R&O&V&M&F&R&P&S&O&H&[&E&O&X&M&H&S&P&D&H&F&R&P&S&R&V&M&R&K&H  
 E&R&P&D&V&F&R&P&S&R&Q&W&H&V&H&F&R&Q&E&D&F&N&I&V&M&H&D&Q&H&H S&R&O&P&H&I&D&E&Q S&R&F&H&V&@  
 ,&R&E&M&D&E&H&P&D&[&E&X&P&O&I&X&S&R&F&M&Q&D&V&S&R&O&V&M&R&E&R&P&D&V&V&H&Y&H&D&O&H&D&M&H&V  
 P&X&V&M&E&H F&K&D&D&F&M&H&C&Q&H&S&E&F&H&V&V @ &M&H&R&S&H&D&E&R&P&S&H&D&M&H&Q&H&E&H&F&R&O&O&H&G  
 S&H&F&M&H&O&D&E&X&Q &R&&M&H&P&R&M&H&F&R&Q&H&H&E&R&P&D&V&V&H&H&C&M&F&N&M&H&D&F&M&O&H&V&V&K&D&Q  
 M&H&S&D&E&O&H&V&H&R&E&R&P&D&V&D&M&S&H M&D&F&M&N&E&D&O&O&H&V&V&K&D&Q H&J P&P R&O&X&E&H&G&H&G  
 M&H&M&K&K&H D&Q X&S&D&M&H&D&S&G H&P&R&Y&D&O&D&M&D&Q&I&K&H&P&R&Y D&O&E&H&E&R&F&K&D&U D&Q D&V&W  
 Y&D&S&R&X&M&R&R&O&D&M&D&H&Q&H&E&W P&Q&H M&H&M&H&P&D&O&F&D&F&N&Q 7K&H&S&D&E&O&H&V&H&M&R&R&M&H&P&R&V&W  
 E&S&R&D&V&I&S&D&D&P&H&M&D&V&S&R&O&V&M&R&E&R&P&D&V&V&%&H&Q&M&H&W D&O&@ Q&H&V&D&M&S&H&H&H&F&M  
 S&D&E&O&H&V&H&V&R&M&H&S&R&F&H&V&V&D&M&D&Q&H&S&R&F&W H&O&G&D&Q R&X&Q&D&M&H&H&T&X&H&G&H&D&Q  
 H&Y&R&O&D&M&D&E&H&D&V&H&O&V&M&H&S&D&E&O&H&V&H&E&H&D&V&Q 7K&H&K&H&D&S&H&Q&M&R&E&R&P&D&V&V  
 S&D&E&O&H&V&R&F&F&X&V&R&P&M&H&V&X&D&F&H&M&D&Q&H&U Q&M&H&S&D&E&O&H&F&R&H E&K&H&D&F&R&Q&F&M&Q @ 7K&X&V  
 M&H&D&S&S&E&S&D&M&S&D&E&O&H&V&H&V&D&O E&H&D&S&H&H&T&X&M&M&H&Q&X&H&D&D&S&G K&H&D&Q&W &Q E&R&P&D&V&D&V&W  
 S&R&O&V&M  
 \$ S&D&E&O&H&V&H&S&P&D&O\ &M&P&Q V&M&K&H&D&I&K&S&R&E&R&P&D&V&D&M&H&F&R&P&S&R&V&M&S&R&J&H&V V Q  
 E&R&P&D&V&S&R&O&V&M D&P&D&M&H&P&D&E&D&O&P&R&E&O&M&S&H&E&W K&H&D&M&S&H&R&E&X&O&N&E&R&P&D&V&V&M&H&V&D&E&O&H&E&X&W  
 H&O&H&Y&D&Q&M&M&H M&O&D&F&N&E&H&[&H&S&R&Q&O&F&D&Q&M&M &M&H&S&R&S&X&O&D&E&M&D&O&D&E&H&D&S&S&R&D&E&K&K M  
 D&S&S&O&H&M&M&H&S&D&E&X&O&D&M&P&D&M&D&O&V&P&R&E&O&O&Q S&R&F&H&V&V&H&V&F&E&L&M&H&S&E&S&H&V&H&Y&R&O&X&E&R&D&J&R&X&S  
 R&S&D&E&O&H&V&K&Y&D&I&H&V D&V&M&H&K&E&R&I E&H&D&S&R&V&E&Q @ 7K&H&S&R&S&X&O&D&E&M&D&O&D&E&H  
 H&T&X&D&E&M&Z&H&H&M&O\ S&H&V&H&M&G&E&+&X&O&E&X&M&D&W @ Q F&D&O&F&X&O&D&M&H&S&D&E&O&H&V&H  
 M&E&X&E&Q R&M&H&G&S&H&V&H&S&K&D&V&H 6&E&H&M&H&H 3&R&S&X&O&D&E&M&D&O&D&E&H&O&R&E&O&3%&0 K&D&V&E&H&H&Q  
 S&R&S&X&O&D&E&M&F&H&S&D&E&O&H&V Q S&R&F&H&V&V&P&R&E&O&O&H&J M&H&J&D&Q&O&D&E&Q> @ D&E&M&D&O&I&D&E&Q  
 @ S&R&F&H&V&M&M&H&V&D&M&M&H D&R&I F&K&D&Q&H&Q E&R&P&D&V&S&D&E&O&H&V&H&G&E&X&E&Q %&D&V&L  
 P&H&F&K&D&Q&P&V&R&M&H&3%&0&R&H&Y&R&O&X&E&R&M&H&S&D&E&O&H&V&H&G&E&X&E&M&Q&H&Q&F&O&H&D&M&M&W  
 D&J&J&H&J&D&M&Q&H&D&N&D&J&H @ ,&M&H&M&H&E&R&F&K&H&P&E&D&O&F&R&Q&H&V&R&M&H&F&K&D&Q Q M&H&E&R&P&D&V&S&D&E&O&H  
 V&H&H&V&X&O&V&R&P&M&H&S&D&E&O&H&Y&R&O&X&P&H&V&K&N&D&J&H&D&Q&F&K&D&E&H&D&N&D&J&E&H&K&D&Y&R&X&Q  
 E&R&P&S&H&K&H&Q&L&H&X&H&V&M&D&R&M&H&E&R&P&D&V&S&R&O&V&M&N&E&W&S&O&D&V&D&S&R&D&E&O&H&Q

QHVDPDQHDVQHPHFKDQPKFKFRQXWMDPRHDFFXDMPRHORU  
 HDFMVIQSRFHVV RSEYDMQHERXSOHNS/EXODEMQ > @ 0DNQHEW  
 PRHOVKDYHEHHQSRVHSEVFEHERPDVVSROVMNEHW 7 KHVTDHMMHDFEQ  
 6)25PRBOK DVEHHQVHBOXHMW VESOEMKRZYHW MDQPSDOPRHOOPMW  
 DVTDHDFEQMDVTDHDFMDMQU \ @ XHW OKH VMRIKHDPRHODSSOHW  
 HVFEHMMHDPDOFRPSRVMEQEV VRVROKHOWMHEXMOFMDW HQIPRHO  
 \$ > @ ,WKDVEHHQVHEDQOVHMMHDPDOFRPSRVMEQNEHW RVROKHOV  
 FOXD ERPDVVDW OIRFHOOXORVEFRPSRQRDQDVKDOHDVHSODVROPHHW  
 @ 7KHPRHODVVXPHVMDERPDVVSROVMNHVDODIHQPEHRHSHHQDDOOHOMW  
 RHRU QWRHDFEQ VMMHRQFMDMHHVHDOHFVDDMQRHERQ  
 VMWVRI ERPDVWSHFQ DQ MDWHBHQHQMMDMHHFDQHEVFEHED  
 FRMRXVMEXMEQ HJDXVVDQJMEHEXOOMEXMEQ @  
 7KHXOEMREMHFMMWKN MMYHORS DPRHODPHENKEK FDQVEXODMMH  
 SROVM/SRFHVVRERPDVVMVHMEXME SHEV HDOEH W SDEOH  
 MPSHDMHEXMEQ KEK XSDWYROXPHDYHDJHMPSHDMHMQ MRKHPDONHEW  
 PRHODMDFKMHVMS KHDKSEHRERPDVV SDEOHVMD VHEXMEKEM  
 KHOSRMMHVIRSRQVMHDFM DQMPQEQ RRSMDOHHGEMFNSDEOH VJHV

ORHOHVFSMQ

,NSDMDHOHMOPRHOIDPHENXOHEMDMMORSHW  
 MPNDHMLQ SDMDHSROMSRHMSEHGMDQ SMPHRIIHHMMW DMH  
 GEMRESDMDH OHMOPRHOLSUPDUORPSUMRIPDKMDVRQHEU  
 RMDERQ HTNRCK DHRPSHMMOHEHEGHERQ LM KZ W  
 DORLURI3% RSOHERHO RHOLSWTKHSDMDHMHGEMRQRQU  
 RQRESDMDHMPSHDMSROVMPSHDMDSMDHMMQHEF  
 SDDPHVMQ MMMSDDPHMMPDORMHDEPHMSLMDMDHED  
 K HSDMDOGIHHQDOHTNRQMSDMDHMDMDMDHGHMMHCOMED  
 ILQMKORHPHMMSEILOHRISDMDHMPSHDMMDHMSCHQHRHG  
 3%0MXVHSSHVHMDHOHVHMEXMEVDPSOL DMQPEHRI HHGMFNVKHMDM  
 RB%0MHVFEHQHFEQ 7E HMQHEVPRHOV 1RQMRKHPDOMQ DQ  
 MRXW \$DHFRRXSOHMPDVVFRQHVDEMTXDMQMFKDDFMHMMHFKHPEDOHDFEQ  
 NEWVRERPDV VSROVM7KHSROVMNEHWKORERPDVVSROVMHVFEHG  
 QHFEQ 7KHQPHEDOFDOFXODMDQHFDRXVHRODPDMHPDED VRMH  
 VMMP 7KHMYROXPHDSSRDFKMXVHVMVROYHMMHMFQHVDEMTXD MQ HODV KH







$$\dot{W}_{NL} = r \frac{\dot{I}_A}{a_p} L r$$

$$\dot{W}_{NL} = 4 \frac{\dot{I}_A}{a_p} L G_{\text{cdd}} \frac{\delta \dot{I}_A}{N} F \hat{a} k_6^8 F 6_a^8 o$$

7KHHHFMMHPDOKHDDWHERHEHMVFEHCV(T @

$$G_{\text{cdd}} L \beta H G_s E : s F \beta ; H G_{/4} E \hat{i} H G_f E \text{ su } \hat{a} \hat{e} 6_a^7 H \hat{i} \hat{n}$$

KHH  $\beta$  P %P % KEKLVHDERKWHFXHDPDPVVPDVVMMHDOOPDVV 7KHSDDPHMM  
 MWHORFDOSRREVMWHERPDVVSDEVOHKEKMHODMHWHDHGYRODDMDMQ  
 SRFHVH@ ,WDHVDVDOHDHODMOKSKKHFROCHVRSRFHVV

$$\hat{i} L \hat{i}_4 E : s F \hat{i}_4 ; \dot{U}_{E::} \hat{E}_4 F : \hat{E} ; E \dot{U}_{\hat{i}::} \hat{i}_4 F : \hat{i} ; E \dot{U}_{/4::} /4 F : /4 ; ?$$

KHH =<sub>Q</sub> =<sub>Z</sub> DQ =<sub>G</sub> DHMHPHQHQHVVSDDPHMWSDEVOHVKNQDJH&HDFK  
 FROHVRSRFHVVVHV<sub>Q</sub> Z DQ<sub>G</sub> DHMHPDVVDFMOWH W7KHSIDVOHYROXPHYDHV  
 QM FROHVRSRFHVVVDFROCHHSPKHMOPDVV FROHVDECKEKPHDQMH  
 QOSDEVOHYROXPHFDQHVROYHSPMDOHV&HERPDVVPDVV

$$8_E L \frac{:5? ; ; 3, \dot{I}_A, ? \hat{a} \hat{a} 3}{:5? ; ; 3}$$

7KHYDOXHVRMWHODMWDDEOHVMHVHHTXDMDHJLHDEOH(ESHHDQVHXEH  
 RXXQ ä

EH ~~MM~~

Properties used in model					
$\rho_B$	Density	700	kg m <sup>-3</sup>		[39]
$X_{M0}$	Moisture content (M)	8.17	wt. %		
$X_{V0}$	Volatile matter (VM)	79.22	wt. %		
$X_{C0}$	Fixed carbon (FC)	10.59	wt. %		
$X_A$	Ash	2.020	wt. %		
$v_{\text{vola}}$	VM/(1- M)	0.862	-		
$v_{\text{char}}$	FC/(1- M)	0.115	-		
$C_{p(B)}$	Heat Capacity of biomass	1112 + 4.85×(T <sub>p</sub> -273)	kJ .		[40]
$C_{p(V)}$	Heat Capacity of volatile	1050 + 0.18×(T <sub>p</sub> -273)	kJ .		
$C_{p(C)}$	Heat Capacity of char	1390 + 0.36×(T <sub>p</sub> -273)	kJ .		@
$C_{p(M)}$	Heat Capacity of moisture	4280	kJ .		
Kinetic parameters for devolatilisation					
A	Pre-exponential factor	1.1291×10 <sup>16</sup>	s <sup>-1</sup>		
E	Activation energy	189.15	kJ mol <sup>-1</sup>		
Kinetic parameters for drying					
A	Pre-exponential factor	6×10 <sup>5</sup>	s <sup>-1</sup>		[42]
E	Activation energy	48.22	kJ mol <sup>-1</sup>		[42]
Thermal properties					

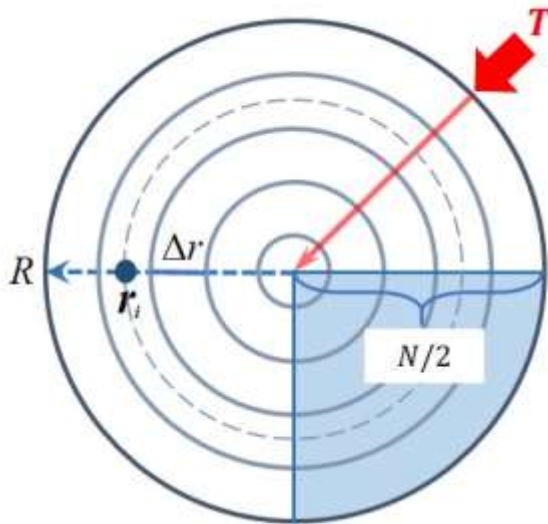
$k_M$	Thermal conductivity (moisture)	0.653	$w m^{-1} K^{-1}$	[38, 43]
$k_V$	Thermal conductivity (volatile)	0.2	$w m^{-1} K^{-1}$	[38]
$k_C$	Thermal conductivity (char)	0.15	$w m^{-1} K^{-1}$	[38]
$k_A$	Thermal conductivity (ash)	0.1	$w m^{-1} K^{-1}$	[38]
$k_B$	Thermal conductivity (biomass)	0.21	$w m^{-1} K^{-1}$	[44]
$\dot{q}_m$	Reaction heat (moisture)	-270	N-NJ	[37, 45]
$\dot{q}_v$	Reaction heat (volatile)	-418	N-NJ	[37]
$\dot{q}_c$	Reaction heat (char)	-418	N-NJ	[37]
Other values				
$\epsilon$	Pore emissivity	1	-	[43]
$l_{pore}$	Pore size	$5 \times 10^{-5}$	m	[38]
1	Stefan-Boltzmann constant	$5.67 \times 10^{-8}$	$w m^{-2} K^{-4}$	[46]

3HYRXWME VNH[SORHWHHHQHVEHHHQHQ MRRWHPDOPRHOQVHVRWHPDO  
 PRHODHDYDDDEOHQHONHDMH @ 7KHMRRWHPDOPRHOQJOHFMMHW SDEOHKHDW  
 MQRERPDVVSDEOHV @ 7KHMRRWHPDOPRHOVKRZOHHDVREQEOHSROVMEHKDYRXRU  
 VPDORRDPVVSDEOHV%RMPHKKOHRODIHSDEOHV%KHMRRWHPDOPRHO  
 SHEMOVKRWHDFMFRPSDHEWMMHPDOO\ WEN PRHO @ 7KXVWHRQ  
 MRRWHPDOSDEOHPRHCFDQHFRQHWW JYHPRHDFFXDWEXODMFXOXWMDQH  
 MRRWHPDOPRHO  
 ,MMVXG W HHQ NHV PRHOVRERPDVVSROVM DHFRQHGG 7DEOHRQ  
 MRRWHPDOPRHO601RQ MRRWHPDOPRHO6KHQVPRHO  
 7DEOH7KHHVEXODMFRQQ

$R$	$V$	$\theta$	$\beta$	$\tau$	$\delta$

7KHNHWSDDPHMROORQ KHWWRKHKHVNHEW DHOMMQ 7DEOH(RU  
 5HHHQHVRXEHQXQ KHH 5 MWHXQHMDOJDVFRQW PRO 6<sub>a</sub> LVWH  
 KHDMPSHDXMRRWHERPDVVSDEOH )RURQ MRRWHPDOPRHO6<sub>a</sub> XVHVYROXPHDYHDJQ  
 PHWRERVVWHSDEOHHYHMHVMS )LXH VKRZKHWGFHMDRQHHTXDQT  
 QDOHFRQW SDEOHKHDMDHQROXPH DYHDJMPSHDXM MHWEDHW  
 XSMRRWHPDOSRSHW 7KHDOFRQWKRWHVDPSOHVDHDW .DQFDW

Journal Pre-proof



$$T_{t+\Delta t} = \frac{\sum_{i=1}^{i=N/2} (2\pi r_i \times \Delta r \times T_t)}{\pi R^2}$$

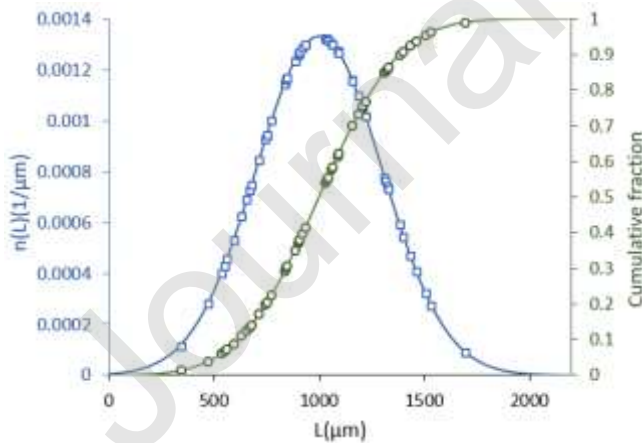
$N$ : the division number of the finite volume approach

$$N = 100$$

Journal Pre-proof

Journal Pre-proof

## 2.2. Population balance model



Journal Pre-proof

$$\dot{a}_a = P \hat{e}_a$$

Journal Pre-proof

$$P_n = P \hat{e}_n$$

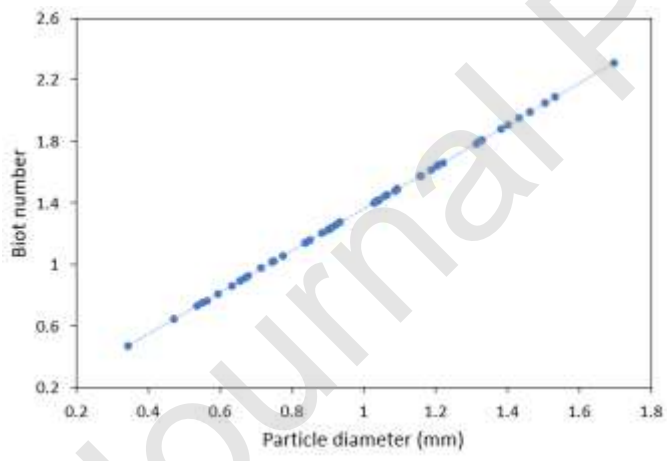
$$J_n$$

RPWHGEXM VQVH0RQDORPHKRG ,QWFKDVEPHKRE VROYHWHHTXDRI  
 SRSXODMDDODQHMVDPSONQPEHRB6QXHEHVDFFXDFDQFRPSXDMQOFRVWHQH  
 QPEHRSDFOHVFKDQHVSRFHVVFH7KHEDVHRVDPSONQPEHPSRYHVVMH  
 SHEMDFFXDFK DHEHDVDFRPSXDMQOFRVWHSRFHVVRSDFOHJRM\

FRDOHVFEH, QVVMHQ XPEHRSDFOHVHPDERQMVWHDSSRSDMVDPSOH  
 QPEHMVXVHMEDODQHDFFXDFDQFRPSXDMQOFRVW  
 7KH%RQPEHU HEG (T MDHQHQHVQPEHKEKHFVEHVWHDERQO  
 KHDVMDQHRDERKEK RFFXVMRXJKFRQFRMHH[MQOKHDMVMDQHRDERG  
 KEKRFFXVMRXJKFRQHFMQ

$$E L \frac{D \cdot \dot{\alpha}}{G'} \quad ;$$

KHH DVMHH[MQOKHDMQHER HEHQ G'MWHHPDOFRQFMW DQ.  $\dot{\alpha}$  MWH  
 FKDDFMVQHQRKHSDEHVSXKHKHDVQHERHEHQVQVHHERQHMM  
 PRHODVVXPHGDOXHVRWHKHDVQHERHEHQVHPDOFRQFMWYHEHHQVHQ  
 FDOFXODVMH%RQPEHU 7KHWHDOSRSHV ZHDVVXPHQVDP .DQ G<sup>3</sup>L  
 P. @ )LXH VKRZWHHODMOKSEHMHQRPEHDSDEOHVHMEHDEOHV  
 FRQHEHMHQHYDOXHVF HVVDVWRXOEHQMG MDQ DHDOSRFHVWHHODMOKS  
 EHMHQWH%RQPEHDSDEOHVHMRW QHDVVMKHKHDVQHERHEHQERPDVVM  
 DHFMSDEOHVH



H H H

### 2.3. DEAM model

HQ HTNRQDQ HUNG EDMRROORZQESRW HPDO  
 HRPSRMROIELRPDVLQOMVDODHNEHRILSHHQSDDOOHOILMHDERQ  
 HDKDERQVQVWRHQDQOQOHDERRQHPHIHTHQWU



$$\frac{\dagger \acute{e}}{\dagger P} : P, L F \acute{e}_4 \pm \quad \# \xi \quad H F \frac{1}{46} F \pm \quad \# \xi \quad 1 F \frac{1}{46} P \dagger P I B : ' ; \dagger' \quad : sw;$$

KHH é MHHQW ERPDPVVSDEHOHDEH WQ é<sub>4</sub> MHHQW ERPDPVVSDEHOH

## 5HVXOWDQFXVVRQ

### 3.1. Model validation

HHMORSHRHOIDPHRNLONOLDHFW DRPSDUKRI HSHUBOHFW  
 MHHPSHDMDPORMDHHRQ KRHSRQ HSHLPHQODREMLHRP  
 SROVKISHUBO ZRRSDLVHV@ HSHLPHQDUHRENDO @  
 KOLMD ILHGEHHDUWJ DWK KK MDHQ TMMH ZW DQHOHDOOJHDG  
 IQHMSKOV EHEERKRIERSDVLHSHUBOMSH HDEW SHDQ  
 RIKRELRPDVQ LH GSODVWRPSDUKQHWHHSHLPHQODDVF PRHO  
 SHGERQ ,DHDHMHQIW HSHUBOSHGERQ IRP RQ LY PDOI RHOZKW  
 Ø DQZV PRHODHRQWMS HUPHQODWd' PHDKOHD  
 ELAMUSHGERQDREMHGHIRHV KLQDRIDEFW HDL LV  
 SHRPLDQ RQOOHEERQEQWQ RQMI RQFMLEDDMKDWHU  
 IRPQRQMDRPHY KPDORRQ LH EPRQWV HSRQV  
 EDHUMWML BRFDLQESSHQW KRVRG LQKDH  
 HPSHDMW ± HSHUBOMRIPDQV ODHQILVHSHLPHQODW ZW D  
 OLMMU SHGERQHRPSRMRSHHG

)LXH 3L VHVXDFHMPSHDMH(SHSHLPHQODREMLHRP @ ØP .

)LXH 5HV&HPDVVDFMPP.(SHPHQODMRP+XDQHDO  
80EDMDQOVMDMREMRP6DKXNKDQDO @



)LXH 6JHH&FW RQRPSDMRQKN DJHPRHORP+XDQHDO @ DQHQDO @

### 3.2. Mass losses

RP6HERR6HERQIHHQIWRHODHEVOLMWPNDMWDNRQKI  
 SHDKREMRQPDOMHGWERQDJ RPISHHEMRIPDHPDQDO  
 PRHOOLMMDPMDQIWHK HQPHQKPSDHRMLW

~~W~~H~~P~~R~~F~~K~~H~~P~~E~~D~~O~~F~~R~~Q~~H~~V~~R~~S~~R~~F~~H~~V~~V~~R~~D~~I~~R~~F~~H~~O~~O~~X~~O~~R~~V~~E~~E~~R~~B~~Q~~V~~I~~Q~~H~~S~~D~~E~~O~~H~~H[~~S~~R~~V~~H~~S~~W~~H~~  
~~K~~H~~D~~I~~V~~R~~X~~E~~H~~W~~H~~E~~R~~P~~D~~V~~V~~S~~D~~E~~O~~H~~M~~K~~H~~D~~H~~S~~D~~Q~~H~~M~~P~~S~~H~~D~~W~~H~~D~~Q~~H~~H~~E~~P~~K~~H~~V~~X~~D~~F~~H~~,~~Q~~  
~~W~~H~~K~~H~~D~~I~~V~~R~~F~~H~~V~~V~~W~~H~~E~~R~~P~~D~~V~~V~~S~~D~~E~~O~~H~~M~~H~~F~~R~~P~~S~~R~~V~~H~~E~~K~~O~~H~~S~~R~~E~~F~~I~~Y~~R~~O~~D~~D~~H~~V~~D~~E~~K~~D~~D~~W~~H~~  
~~V~~D~~P~~H~~E~~W~~H~~P~~R~~M~~X~~H~~F~~R~~Q~~Q~~H~~S~~D~~E~~O~~H~~M~~Y~~D~~S~~R~~I~~H~~Q~~V~~K~~R~~V~~S~~H~~E~~G @ 7KHPDVV  
~~O~~R~~V~~V~~D~~W~~R~~K~~S~~R~~O~~V~~L~~V~~D~~H~~V~~W~~O~~H~~S~~H~~Q~~R~~Q~~H~~M~~P~~S~~H~~D~~X~~H~~E~~X~~Q~~H~~W~~H~~E~~R~~P~~D~~V~~V~~  
~~S~~D~~E~~O~~H~~V@

**LH 0 DORDW SHHG G PP.D1RQ LKW DO PRHOZV**  
**1RQLKWPDPRH OZKW**

~~)~~X~~H~~ ~~S~~H~~V~~H~~W~~H~~Q~~E~~D~~O ~~P~~D~~V~~F~~K~~D~~Q~~S~~H~~E~~M~~Q ~~P~~I ~~P~~P ~~V~~S~~K~~H~~E~~D~~O~~E~~R~~P~~D~~V~~V~~S~~D~~E~~K~~E~~K~~  
~~H~~H~~M~~ ~~W~~H~~S~~E~~J~~H~~V~~V~~R~~Q ~~D~~Q ~~H~~Y~~R~~O~~D~~D~~M~~D~~F~~Q~~N~~Q~~V~~H~~W~~ ~~P~~D~~Q~~W~~H~~V~~R~~F~~F~~X~~H~~E~~G~~  
~~E~~R~~P~~D~~V~~V~~V~~S~~R~~O~~V~~M 7K~~H~~H~~R~~H~~W~~H ~~D~~W~~R~~I~~D~~V~~V~~K~~D~~Q~~H~~H~~O~~H~~F~~W~~H~~D~~F~~F~~X~~D~~F~~D~~Q~~S~~W~~H~~D~~E~~D~~M  
~~W~~H~~H~~E~~R~~H~~O~~V 7K~~H~~S~~R~~F~~H~~V~~V~~W~~P~~Q~~W~~T~~X~~E~~O~~O~~H~~V~~V~~W~~D~~Q ~~V~~Q ~~W~~H~~E~~P~~H~~E~~D~~O~~S~~H~~E~~R~~I~~  
~~E~~R~~W~~Q ~~M~~R~~W~~H~~P~~D~~O~~P~~R~~H~~O~~V ~~D~~Q ~~S~~H~~E~~M~~G~~ ~~K~~I~~K~~ ~~G~~H~~Y~~R~~O~~D~~D~~M~~D~~W~~R~~I~~Q~~R~~Q~~~~M~~R~~W~~H~~P~~D~~O~~P~~R~~H~~O~~V  
~~(~~Q ~~D~~S~~S~~H~~D~~W~~V~~H~~F~~R~~Q~~K~~E~~K~~M~~ ~~F~~O~~D~~H~~Q~~ ~~F~~O~~D~~H~~G~~F~~R~~P~~S~~D~~H~~W ~~W~~D~~M~~ ~~R~~Q ~~M~~R~~W~~H~~P~~D~~O~~P~~R~~H~~O~~V  
~~Q~~(Q

~~(~~S~~H~~E~~M~~W~~H~~P~~D~~V~~V~~O~~R~~V~~V~~O~~M~~ ~~M~~R~~H~~O~~R~~Q~~H~~M~~P~~S~~H~~D~~W~~H~~a~~ ~~R~~& ~~M~~V~~K~~R~~Q~~  
~~)~~X~~H~~ (~~R~~E~~H~~H~~H~~E~~H~~ ~~R~~X~~E~~H~~R~~Q~~X~~Q 7K~~H~~E~~H~~D~~V~~H~~R~~H~~O~~R~~Q~~H~~Q~~W~~H~~D~~F~~F~~H~~O~~H~~D~~W~~  
~~W~~H~~P~~D~~O~~H~~J~~D~~O~~R~~Q~~ ~~N~~D~~F~~K~~E~~R~~G~~ ,~~Q~~X~~H~~E~~H~~R~~M~~P~~S~~H~~D~~W~~H~~R~~P~~D~~V~~V~~O~~R~~V~~V~~D~~W~~S~~H~~E~~M~~P~~R~~Q~~  
~~M~~R~~W~~H~~P~~D~~O~~P~~R~~H~~O~~V ~~(~~Q~~P~~P ~~)~~X~~H~~V~~K~~R~~Z~~ ~~W~~H~~H~~[~~W~~Q~~]~~~~H~~H~~E~~~~F~~Q~~E~~H~~Q~~  
~~W~~H~~S~~H~~R~~Q ~~K~~R~~Q~~H~~S~~D~~E~~O~~H~~S~~R~~S~~X~~O~~D~~E~~Q~~



)LXH ,QXHEHRWPSHDVHRQDVVORVVDMSHEMRP RQ MRKHEDOPREOK  
\$OPP

)LXH MHH[WRIV]HH&FQYPH SHRQ RKROHSDEOHSRSXODEQ RQ  
MRKHEDOPREOK \$0

### 3.3. Intra-particle temperature distribution, size reduction and porosity

RE HUH&RQ RQ KZ FRKORMDGDOWPSHDVMEERQMPH  
DWHHRTHU LQSDVH ZW LEMDKHMG RQWPSHDVMDGDO  
GHERQMEHOHSEHHLV OLMHHQEHVHRQWPSHDVMDQH  
WPSHDV RIRSDVHZW L&W WDGDOVPSHDVMEERQSDVHLV  
VPHEDODSDDEROLF KKDQPHLEDMZVDMH

)LXH RQXSORADDOMPSHDWHEEXRYHEDWHRPEHU  
 GP%GP%GP%L E\|RQ MRWHPDCPRHOXQ  
 V W D W  
 N  
 V

)LXH 3DEOHDPHMDSRPYDE WYHQDEVOHVGP%L  
 GP%GP%L WIRQ MRWHPDOMXOE1RQ MRWHPDO  
 PRHOXRXW

**3.4. Population level performance**

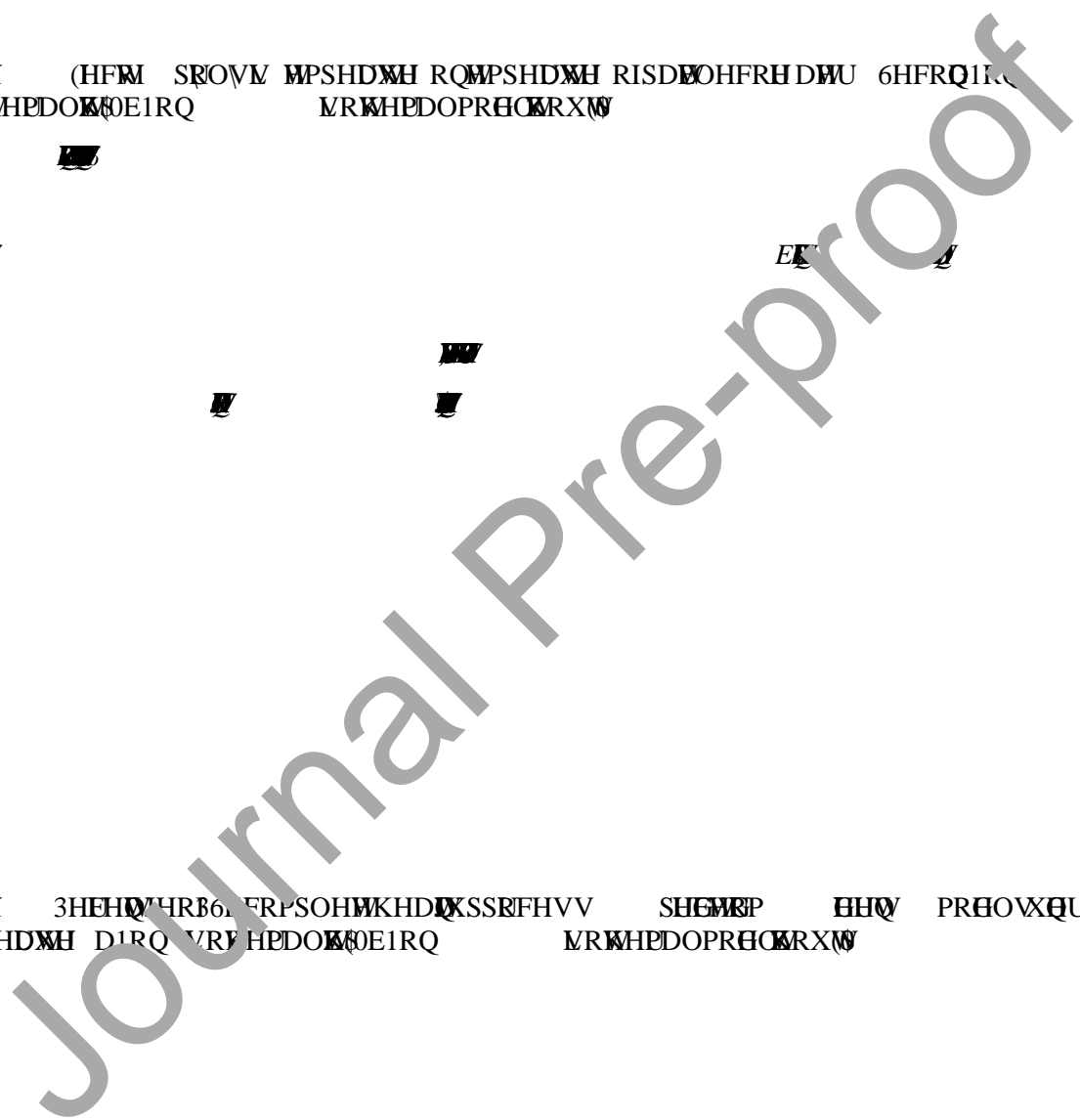


HFOHQ F ~~ME~~HDV ~~IS~~DEOHV ~~I~~H )LXH VKR~~Z~~KIKS~~R~~O~~V~~M~~W~~PSHD~~W~~H~~D~~C~~D~~Q~~H~~V  
KHD~~W~~Q~~H~~R~~X~~J~~K~~W~~S~~D~~E~~O~~H~~

)LXH (HFM SRO~~V~~M ~~M~~PSHD~~W~~H ~~R~~Q~~M~~PSHD~~W~~H RIS~~D~~E~~O~~HFR~~H~~D~~W~~U 6HFRQ~~I~~R~~C~~  
M~~R~~W~~H~~D~~O~~P~~R~~H~~C~~O~~E~~1RQ M~~R~~W~~H~~D~~O~~P~~R~~H~~C~~O~~R~~X~~W~~

~~H~~ ~~ME~~  
~~ME~~  
~~ME~~ ~~EE~~ ~~A~~  
~~ME~~  
~~ME~~ ~~ME~~  
~~ME~~ ~~ME~~  
~~ME~~

)LXH 3HEH~~Q~~HR~~B~~6~~.~~FRPSO~~H~~W~~K~~H~~D~~W~~S~~S~~R~~F~~H~~VV SHE~~M~~RP ~~EH~~Q PR~~H~~O~~V~~X~~Q~~U  
M~~P~~S~~H~~D~~W~~H D~~I~~R~~Q~~ V~~R~~F~~H~~D~~O~~W~~S~~E~~1~~R~~Q~~ M~~R~~W~~H~~D~~O~~P~~R~~H~~C~~O~~R~~X~~W~~





VQHDQEXMSDEOHVHXQHXRQWPSHDWH

)LXH RPSDVRKHDIXSHSEMHHQHDQW  
XQU HHQ WPSHDWH

EXMSDEOHVH

### 3.6. Heating up time of irregular size distribution

,MERHKKHGLQDMMHLQDEOHGIIHHRIEDDQ SAPH  
 EHHQHDQEMSDDHLH ,MERDLPRKHHHLMSDDEH  
 MHGEMRQ KDEQ SAPH SHGERQ LI R V HDDBMHGEX MRI  
 ELRPDMHFN ,WHSRGE\ DQMO PLOOLQDMDPPHPLOOZW  
 DHHQHRIPP EMSDDEHDHDCNPREPKDOOHHMLHQ  
 MFKMTHRISDDEHLMEMRDLH PP DDEW  
 KMDORHHMDHSDDEHMHKEDDHW PPIDOOVPRHO  
 IDPRMORSHRQEDOHGEMRIPSCPHMPPDHSROKIELRPDV  
 ZLHEDMHGEMRQ LI FRPSDHW SHGERQVRIKDDPH EHHQ  
 MQHDQEMG MHCQ LKHPDOZW NHHHHLQONKELW W  
 LPSRMRIRQHUSDEPHLMEMRQDMMRISROVSRHV

)LXH 6HGXMRXQRPDVVPRXJODVPRDQO)HQQHYHDSHWH  
ODRP 7DQXVHDO

)LXH RPSDMRQKHDIXSEHSHENHMHQOHDQEXMSDEVOHVJHXVQ  
IRQVRKHEDOX(0

U V

RHHHEMOMELRPDHHHMHGEMRISRH ELRINOW 30% 0  
RSOHRHOLMPPHMMORSHHSHGF WSKOVKIELRPDSDDHV H30 LMG  
KSHMQ IHHSRSODERRIQPDO MH GAEERQOHDU MFMEMQ 7R  
GIIHNSHPRHOQ LKPEDO ZKVV DHEKQOHRHTMRO  
RIPDDHHRPSDHHPRQMSHGERSHIREPARI MHHRO  
SREMMHQ HDEQ SDPHMSROVSRFKIELRPDMMIGEM RQ  
,MROV

x R W W W W  
W R B W  
W  
x W W W  
W F W  
x W W W  
W  
x R W W  
W

7KHBYIORSRERHOVXFFHVVKOOSHENGFRQHVRSRREDQRI ERPDVYHGMFN  
KDVHMYRQ 7KHEHQEDORXFRPHZOEHVXSSRMHRWHHVIRSOVM  
HDFMMHMPQRSEDOHHCNFNSDEVOHVJHV)XWHYHORSPHQW  
DPHKNMHHQD QPHQSDVOHKDEMROHDMQDFW FHWKERPDVVSDEVOHV  
VKRZJXODVKDSHVKEKKDYHHQXDFHDHDWYROXPHDVK/OHDCWYDQ  
FRQHVRSRREDQHRHSDVOHV 80EDWO\ WSHSERI HDOKDQ XSEH  
RERPDVVADVIHQKDSHCEXMOEHFDOEDMERSRDQ WQSRW  
SKHRPHQWRXJKSRHFKDEQOVDQ RQSDVOHVXDFFRXSOHVXREXQ JDVDRZ





Anthony V. Bridgwater

Junmeng Cai

## Acknowledgement

~~THE~~LDSSHEDWILQDOSS      ~~RE~~WERP      ~~SH~~DERDWI  
5HQZEOHQRN      ~~RE~~WODQSHKRDODLQ  
3RDPPIKROOHRIQHLDKBO6EHKQW

Journal Pre-proof

5HHHQHV

@ RRLWQWHOH33HOVKIKREL RPDREL R RLOBDO  
HLLHNOV

@QHUVWYHW/(PHVRQDODPV&HQH]60RQRHDO  
(HFWERPDPVVWVKHDDWMDQDPSO HVVHRPERZYH HQDDHOVSRQVM  
SR&FWOQDQXDOHVS\$SOHQH  
KDD%KDVNDVFRPSHKHQVHHYHRSRQVVRDIRFHOOXORVE  
ERPDPVV5HDEOH(HU

DL+K %DNV@QKDDHDO5HYHRSKVERFKHPEDO  
SRSHVVDQDQDQDFKDDFMDDRDIRFHOOXORVEERPDPVV5HDEOHDC  
6XVMDQEOH(HU\$HYHZ

@DWSHYHKKDVSROVVRERPDPVVDGR& FWSJDD%RPFVDDQ  
%RHQU

HNQ%KDVNDURQRYD03RFHVVBHYHORSPHQDWRDVSROV  
WFKRORJHVRWHPDQDFWHRHQDEOHDDSRMHOVVRPERDPVV5HDEOHDC  
6XVMDQEOH(HU\$HYHZ

DR16SD4XDQKHPRJYDPEDDQVMDSRQVMSR&FW  
FKDDFMDDMPXESDOVRODVMXVVOXCHODVKDVDV(XH

DR1.DPDQXDQDODPV37KHPRFKHPEDOFROHVL RQVHJHVOXCH  
BDOHYHZRJVHVVQHDDPEXVBFHGH

DR1-DDR0D=4XDQDTY650RHODDQEXODRFXDQDHC  
SRQVMDQVEDRROVVOXCHQDNDQXHC

EDDQDR1XDQ(SHPHQOVMSRQVMDVE)RI  
ERPDPVDSODVWRVSR&FMQHQKDC VXSRRDDOVWHPEDO  
(QHQRXQD  
QPEDQYHVMHZ RERPDPVVSROV(HU6RXEHV

9HQERVFK3)DVSRQVMMKROVHYHORSPHQRKHQV  
@DMSKDOOHQHVDDQSRVWVVOVROVVR%RPDPVV3DW

-RKQRQWHYHFKR05 HY

@HQML6PW.6HDSIQ00-)LKHQ(HFMSDEOHVHRQRZ

MPSHDMSRQVMPKRRPLVV(HDDQXHOV

QRXQORZ-7KH3RSXODDQDODDHDVD7RROR&HVVDDDEOH 5DW  
3RFHVVBHV.21\$R7DQDEOH-RXQD

@XOEXW0W6.PHSREOHPVSDHOHFKRORJVDVDDOPHFKDQDQ  
RXPOLVWHPEDQ(HHQFHH

QKDPV R6.YLWHRQK;

1NODVVRQMRXQORZ-HDD

QOVVRPHRVFDOHHHFVQIK VKHDIDQDQMRXJKDFRPSXDDQDQXG

QPEV -SRSXODDQDODDQHRXSOHERPSDDHRRHO3DEXRORJ\

@-RXQORZ-5HRQZ:5HSHVHQ

QSDVRRHFRVVDRDQDQO

PIHERPSDDHQKIKVKHDIDQDQMRXJKDFRPSXDDQDQXG

@-RXQORZ-5HRQZ:5DVPXVRSQDODVVRQMDKDPVVRQ\$

FRPSDDHQDQ& 3%0PRHORKIKVKHDQW DQDQDQ(-RXQD

QRXQORZ-5DQO5/0DVKDDO095FHMSSRSXODDQDODDQHRQFOHDMQ

JRMDQJHJDM(-RXDQ  
 0%0RVEDFK66FKPXKD6KXDL+XDQW 0RHOODVRRW  
 RPDMPDODPVQJDVROHFHFHFHQXVQDHMDHGRSXODEQ  
 EDODQHPRHOSSOHQU  
 HOODV0DYEVVRQ/DHOKO76MVE3HVVVRQ%3ROVMRDDIH  
 RRSDE/ OHVVMKNDJHPSRDEHQEXODEQ)XHO  
 %3DSDNV.X6)DOJR%/RQKXVWEHDOAPRHOODRSDHOH  
 VKNDJHQDXHGHRRERPDVVDVSRQVMWTXDDWHPHWRPRPHQ W  
 )XHO3RFHV7HFKRO  
 ODVRRHOQFKHPEDODSKVEDOSRFHVVHVRRRORPDVVSROVM  
 3RJVHVQUDEPEXVMGFHQ  
 RXJK%5%HFNBFKDZ3DHQSSOEDERP DFKHOHDW  
 SROVMHDFRQANV5H&FQPRHOVROXMMHMHQEOHSRFHVVRSEMDRQ  
 RPSXWDRHPEDO(QHQ  
 KDPDSDHNN9=KDD%RPDVVSRQVM 2 NYHPRHOODSRFHVV  
 SDDPHMDQDQVWV5HQZDEOHDGXVMDQEOH(QU)HYHZ

QDQ)3DEKDD+RQHD02YHMHKFRPSXMDQODXG  
 QPEVVEXODMRHDFRU VFDHERPDVV3ROVM6XVMDQECHHPM W  
 (QHQ  
 XQDP\$OREDO&HPEDO.FEVRJRVD)XHOV+RMRHOODRMDQ  
 3ROVM6SDHMDQO3XEOMKD  
 DLXK5DYHMHKEXMDFMDHQIPRHODW  
 DSSEDMHSROVMROIRFHOOXORVEERPDVV5HFECHDQXMDQEOH(QU  
 5HYHZ  
 QHLDQHFMDQHREETHVRRQHTXHQOSROVM  
 NHEVRRIDQVRODZVWVXVQWHPRJDPH QOVMDQEXMDFMDQ  
 HQIPRHO%RHVRXVHFKRO  
 QNRYE%-RYDRYE-2VME6SMHYE%FEDDOVRRQ MRWHPDO  
 EKORRSRODFODEFG JHODRQXOXVQEXMDFMDW RQU  
 PRHO-RXQORTKHEDODQOVMDQOPHW  
 QDQHLKDD/K%HD07KHRHEDQOVRRXEOH  
 /RJMEXHMDRQURHORLKLCHFRPSRVMDRWR6ROG  
 )XHOVQVDO(QHQKHPZVVDK  
 DLK51HEEXMDFMDFUPRE01XPHEDOVROXMQQ  
 DSSOEDMSROVMNWRVRPHSVHVRERPDVV%RHVRXVHFKRO

DL X/K5+XEHX MDFMDHQIPRHORWHSROVM  
 ROIRFHOOXORVEERPDVVHHPHW  
 ROVWRQXPHHWRQOYHRRPSXMDQO0HWRGQ  
 (QPHQ)QXDFKDDQ FV%HOQHGOEHL6SH%HOQHGOEHL5

EDXOORXHB'DWRQRVVDQHOFK6KDDFMIDERPDVV  
 FRPEXVMQMKWPSHDWVVEDVHROQSDHGOHSDHOHPRHOSSO(QU

ODVHDFRPHNPDPVVMQSRWRXJKDVKNQERPDVVSDHOH  
 H[SRVHWRWHPDODDQHPEDO(QHQGFHQ  
 %6KDD16KHQDQ-0D/,-RQV-0HDORPEXVMRI D  
 6QH3DEOHR%RPDVV(QU  
 EDXOORXHB'DWRQRVVDQHOFK63HEMKIK

MPSHDWHDSEPEXVMDHKDYRXXRERPDPVSDFOHV)XHO  
 EFR(%DOFOVM DQREOORRROVM&HPEDO(QHQ  
 6FHQH  
 @XRSDDQVSDSDQNRV10DVFKR\*XFFKHVORHOORRHSROVM  
 RERPDPVSDFOHV6XHVRRQHEW&HPDODQHDVQHHHFVWKH&DQO  
 -RXDOR&HPEDO(QHQ  
 @XDQDQ3/7DQHQ-ORHOQDQSHPHQO  
 6XHVRRKH(HFWRROXPH6KNDJHRQH3ROVMRDVRR6SKHH(HU  
 )XHOV  
 @DQ : &HOERQHJH%ORHOODQ[SHPHQOYHEDQR  
 SKVEDODQKHPEDOSRFHVHV&SRROVMRDODIHERPDVSDFOHV)XHO

@OJDR%ODVRRHOIRREJDDQKH8HDFMG &H 6KND  
 \$\$SE[EDM@VVO(QHQKHPM/VHVHDEK  
 @RRR-EDD(ROOD]R-3DVRORIQRRHORRRPEXVRR  
 /DIH3DFOHVRHQRRR(HU)XHOV  
 @DNMS %DXP+([SHPHQODQRRHEODQHVDRKHDQ  
 PDVVQHSRFHVHV&SRROVM  
 @KDDVM%D[MU5REORSHFWRVSDFOHKHDDQDVVQHRQ  
 ERPDVVHYRODDQDRQSHPHQOHOVXOWD PRHOSHQR(HU)XHOV

@RKDQHQ-HQH@DERL30DEQHEH50EKHOO5((MORRI  
 DSSDHQYRODDMDQHEVRPKHPDOOKMHPDOOKENSDEQVDR  
 HQRRRERG ERPDVV(HU  
 @+5REHMH5SD%%D[MURPSHKHQVHVRRERD'V'DFOH  
 FRPEXVMDHQXHOV

@R+X+DP -RKDQHQK+HQQHERHFMRKHPEDO  
 PRHORHYRODDMDRRKHPEDOO\ KNER'DVSDFOHV  
 @OH'=-DEHDDQHDQHEWQHORRPSHLSRSROVMRRO  
 KHPEDO(QHQFHQH

@-RXQORZ-5HROG:FXDF\ DQSEDOVDPSOQROR  
 VROXRRSRXODQDODQHFTXDR  
 @-DVVDQFRH50DNNDXRRER'DVSRROVMQRQU  
 HDFMHTXLSHMDQYHOJ'V+PQOHSDDM,KHPRFKHPEDOSHUPDQHDQ  
 SR&FW)XHO3RFHVVYHFKRQRJ\

@KDYDQP6DVHEWRM'DVMSROVMXVQEXMG  
 DFMHQHPRHO%RH'RXTHFKRO  
 @XQDP\$OREDQNHQDOVMRFR PSOH[PDMDOV(HU)XHOV  
 @LQKQHQH'W'X'P'J'FMHQHPRHO ±3DW  
 HMDPQIHEDQSDDPHEWWRHVRRXTHFKRO

@KXNDQSW6DKD5.0RH OORRROVMRRODIHERSDFOHV  
 %RHVRXTHFKRO  
 @DXODXVNDV5KJVSMDV1([SHPHQOQHVDRRSHOOHW  
 VHOODQKQKSRROVM)XHO  
 @H]DHL6RNKDQDM6 %LE&DXQPHEDODQ[SHPHQOVRRQ  
 DVSRROVMRMDHRRERPDPVSDFOHV\$\$SO(HU  
 @LXRQ-XDQ%DNV6HMO3RFHVVYHFKRJDYHEW  
 DQOVMDRMRFRQHVR QONHEDQOVRRDIRFHOOXORVEERPDPVSDFOVMVH  
 VRRFRQDQON5HHEOHDQXVMDQEOH(HU)HYHZ  
 @R+X+DP -RKDQHQHDQHERHFMRKHPEDOPRORU

HYRODDJDERKHPD OOKENERPDVVSDVFOHV6WFNKROP7HFKEO8QHVM  
 HPDN  
 0XW0HONR76DOYD66REHD0)DVVROO5YKFF6HDO  
 3ROVVR7KEN%RPDVV3DFOHV([SHEHQODQW0RHOOKKHPEDO  
 (QHU QDQDFRQ  
 0SDSN.X6%QWFKDXVH\$SSOEDRQWPREHODVW  
 SROVVRERPDVV)XHO3RFHVVV7HFKRORJ\  
 0HQML6PW6HDSIOD0-)MKH0(HFMDEOH6 IHRQZ  
 7HPSHDXH3ROVLRRR%RPDVV(H)XHOV  
 0Q0H VHOVNB1DZRZ 2HORHOIRIQO+HDWQHQ  
 %RPDVV3DFOH3ROV(H)XHOV  
 0QXV./DP36 6RNKDQDM6BFH-53KVEDOSESHWVRDRZ  
 FKDDFMIDRIRXORRPDVVRP6XJODVR6D6XKODM6FHEHDQ  
 7HFKRORJ\

Journal Pre-proof