Simulations of agglomerate sedimentation and suspension

150 1363 AP 1.1/1.2

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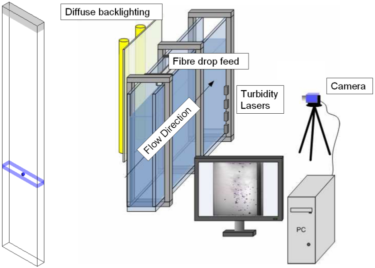
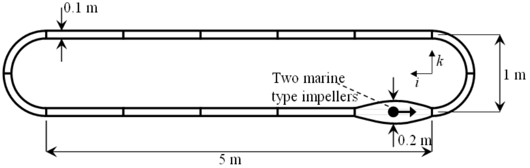
Motivation

To improve and validate the modelling of fibre agglomerates

- sedimentation in the rectangular column
- sedimentation in the whole channel
- suspension in the whole channel

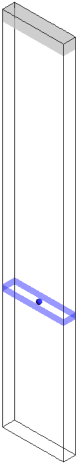




Column sedimentation

Solver specifications

- Two flow models with 10 dispersed phases
  - + 10 Algebraic slip mixture phases
  - + combined Eulerian (1)/Mixture model (9) dispersed phases + 1 constraint phase
- Schiller-Naumann drag coefficient and turbulence dispersion coefficient of 1
- No agglomeration or breakage
- 2-way coupling
- No mixing models applied between the dispersed phases
- Continuous phase turbulence modelled by SST
- Coarse mesh
- ~21.9 g of steam-blasted MD2 or MDK
- Particle diameter (constant at 2.5 mm)
- Fibre agglomerate mixture viscosity: $\mu_r = 1 + 2.5r_p + 7.6r_p^2$
- Initialised with zero velocity field
- Convergence criterion was set at $1.2*10^{-3}$ for combined model
- Transient of 300 s with timesteps of
  EMM-ASM:
  `if(ddt<=0.1 [s], 0.001 [s], if(t=<100 [s], 0.005 [s], 0.01 [s]))`
  ASM:
  `if(ddt<=0.049 [s], 0.005 [s], if(t=<0.999 [s], 0.01[s],if(t=<1.999 [s], 0.05[s], 0.1 [s])))`



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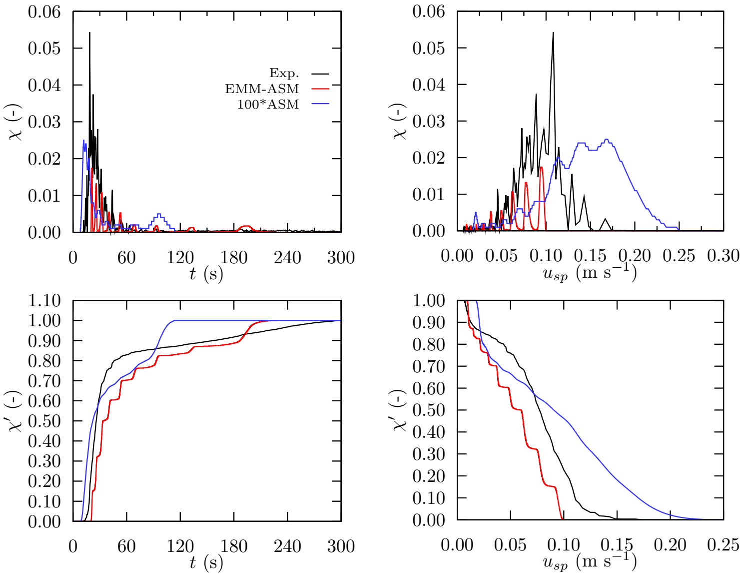
Column sedimentation

MDK Results



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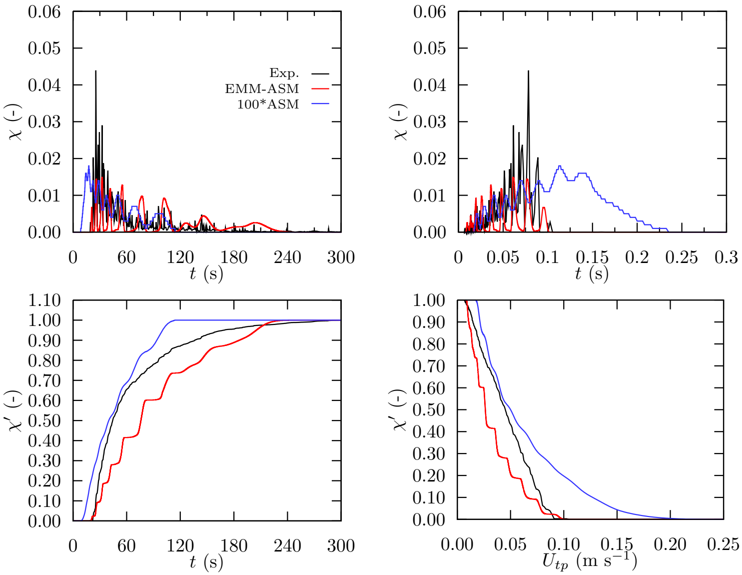
Column sedimentation

MD2 Results



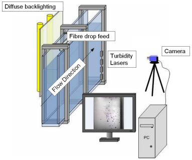
Conclusions

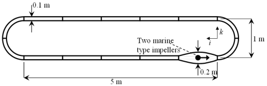
- ASM model settling velocities are faster than the combined model
- Combined EMM-ASM model are better at reproducing the settling velocities
- Higher velocity fractions take longer to converge
- Possible improvements
  - include using a second Eulerian phase to split the heavier phases from the lighter phases
  - fewer mixture phases

Channel sedimentation

Solver specifications

- One Eulerian dispersed phase
- $\sim$ 21.9 g of MDK
- $d_p = 5$ mm, $\rho_p = 1027$ kg m^{-3} & $\mu_{rf} = 1 + 2.5 r_p + 7.6 r_p^2$
- Continuous phase turbulence modelled by SST
- Transient of 10 s with `if(t<=0.5 [s], 0.0025 [s], 0.005 [s])`
- Initialised by interpolation of a transient solution of single-phase flow
- Mean velocity of 0.2 m s^{-1} given by 1290 kg m^{-2} s^{-2} momentum sources at 0.305 and 0.68 m (Darcy-Weisbach equation)
- Schiller-Naumann drag coefficient and turbulence dispersion coefficient of 1
- No agglomeration or breakage

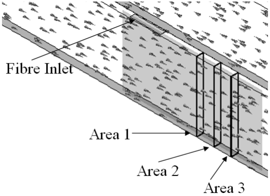




- Inlet conditions:
  + velocity, normal to the inlet
  + estimated via Laws of Motion and an assumed drop
  + Injection functions:

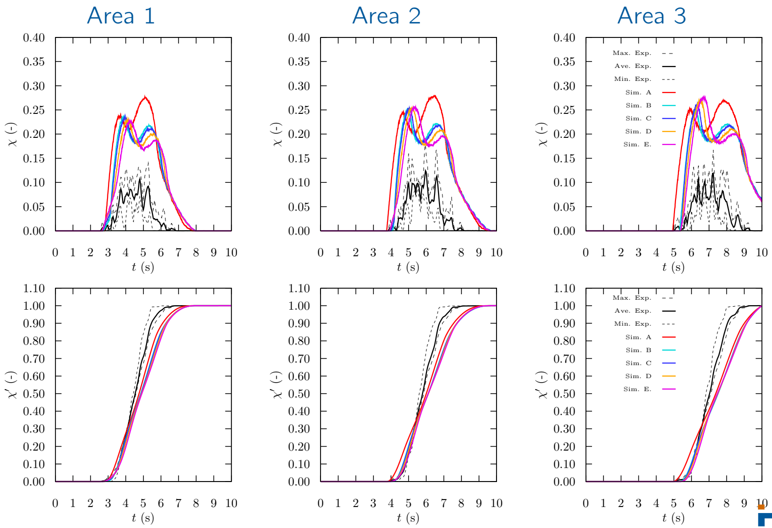
```
velinlet = if(t<=Ti, Ui, 0 [m s^-1])
vfin = if(t<=Ti, 0.664, 0)
```

Sim.	A	B	C	D	E
Ti (s)	0.0150	0.0275	0.0325	0.0450	0.0650
Ui (m s^{-1})	2.083	1.052	0.897	0.662	0.481



Channel sedimentation

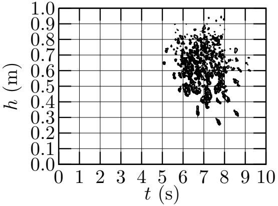
Traces for cases A-E of the fraction of the volume integrals of the fibre volume fraction to the volumes



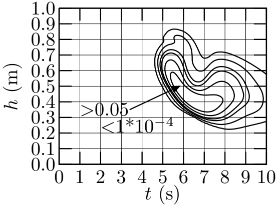
Channel sedimentation

Sequential profiles of the fraction at Area 3

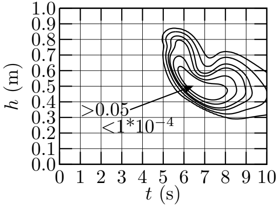
Exp



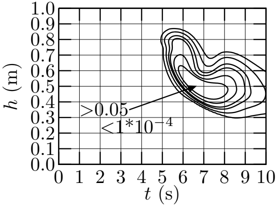
Sim. A



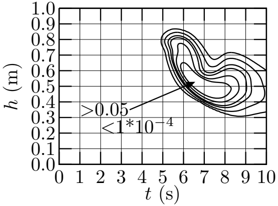
Sim. B



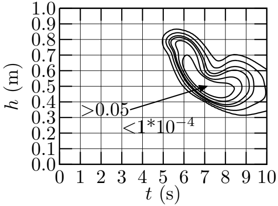
Sim. C



Sim. D



Sim. E



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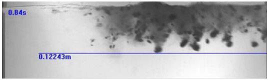
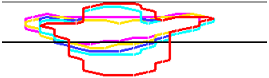
Channel sedimentation

Contours for Sims. A-E

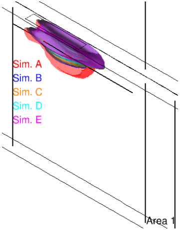
Flow Image at 0.84 s



Contours at 1%

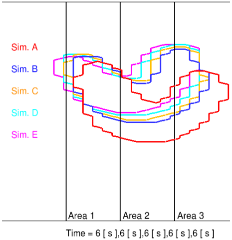


Isocontours at 1%

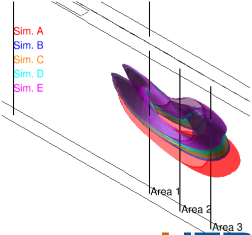


Flow Image at 6.00 s

Contours at 1%



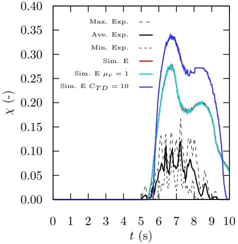
Isocontours at 1%

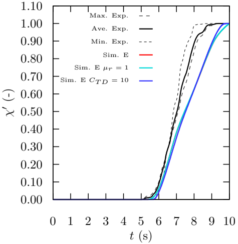


Channel sedimentation

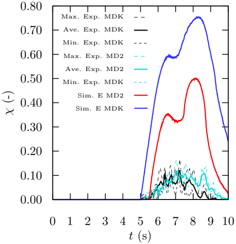
Traces for modifications to Sim. E of the fraction of the volume integrals of the fibre volume fraction to the volumes

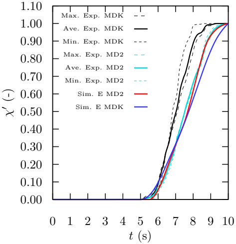
Single dispersed phase





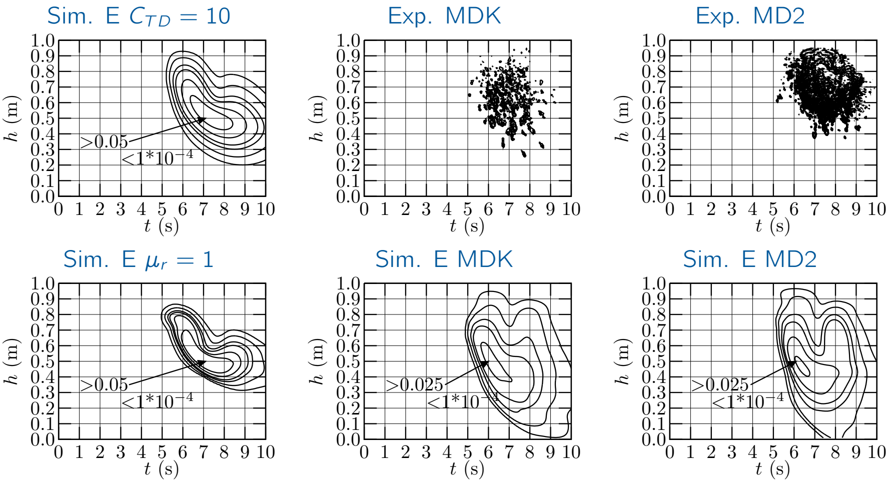
Ten dispersed phases





Channel sedimentation

Sequential profiles of the fraction at Area 3, where parameters in Sim. E are varied

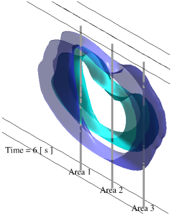


Channel sedimentation

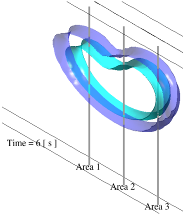
Contours for variation of parameters in Sim. E

MD2 Flow Image at 6.00 s

Isocontours Sim. E MD2

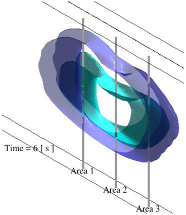


Isocontours Sim. E $C_{TD} = 10$

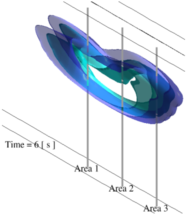


MDK Flow Image at 6.00 s

Isocontours Sim. E MDK



Isocontours Sim. E $\mu_r = 1$



Channel sedimentation

Conclusions

- Sedimentation simulations physically agree with experimental traces in terms of time
- Trace form differs with initial condition and C_{TD}
- Agglomerate spread changes with C_{TD} for both channel width and height
- Image after 6 s shows a spread agglomerate sizes with small agglomerates closer to the top of the channel
- However, sedimentation rate of the agglomrate cloud corresponds to the heavier agglomerates
- Simulations with the combined EMM-ASM model and the respective MD2 and MDK fractions show similar effects to the single phase definition, but the spread is larger with slower phases remaining at the top and faster phases sinking further than the experiments, particular for MD2

Channel suspension

Solver specifications

- One Eulerian dispersed phase
- Steady state mode
- Continuous phase turbulence modelled by SST
- Volume-weighted body forces and coupled volume fraction equations (correction step)
- Two domains with mean velocity of ∼0.5 m s^{-1}
  - straight section with uniform velocity condition
  - whole channel with momentum sources of 6227 kg m^{-2} s^{-2} at 0.33 and 0.66 m (Darcy-Weisbach equation)
- ∼ 441.7 g of MDK
- Schiller-Naumann drag coefficient and turbulence dispersion coefficient of 1
- No agglomeration or breakage
- Strong convergence criteria
  - maximum residuals less than 10^{-4}
  - less than ±3% change in volume fraction traces
- Density and diameter adjusted to give terminal velocities of fine, light and heavy fibre phases

Phase	pF	pL	pH	c
Description	Fine fibre agglomerate	Light fibre agglomerate	Heavy fibre agglomerate	Continuous water
$U_{j,up}$ (mm s^{-1})	∼0.5	∼20	∼50	-
d_p (mm)	0.5	5	5	-
ρ_p (kg m^{-3})	1002	1002	1027	997
μ (kg m^{-1} s^{-1})	$\mu_c\mu_r$	$\mu_c\mu_r$	$\mu_c\mu_r$	8.899*10^{-4}
ζ_p	0.0166	0.0166	0.0028	-
r_p	0.0626	0.0626	0.01046	$1 - r_{pX}$

$$U_{j,up} = \frac{4}{3} g_j \frac{\rho_p - \rho_c}{\rho_c} d_p \frac{1}{C_D}$$

$$\mu_r = 1 + 2.5 r_p + 7.6 r_p^2$$

$$\zeta_p = (\rho_p - \rho_c)(\rho_f - \rho_c)^{-1}$$

$$r_p = m_{p,dry}(\rho_p - \rho_c) V_{Ch}^{-1}$$

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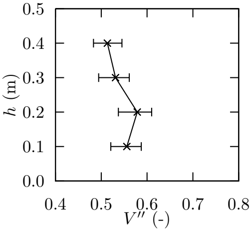
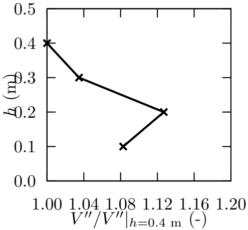
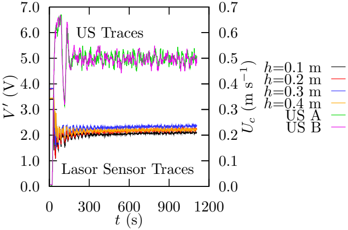
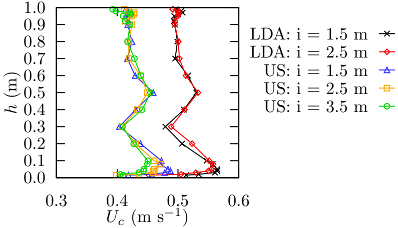
Channel suspension

Experimental studies (1)



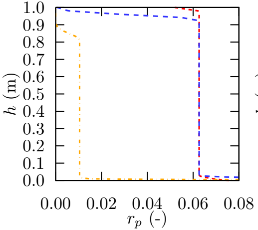


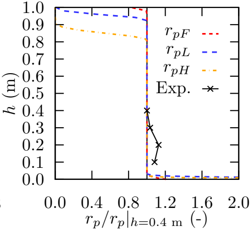


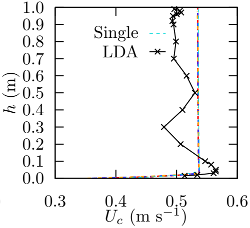


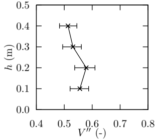
Channel suspension

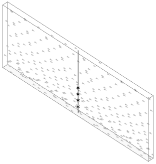
Simulations on a section of the channel







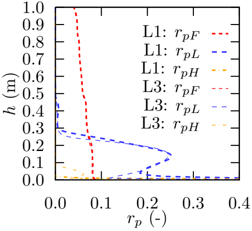


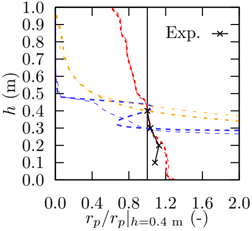


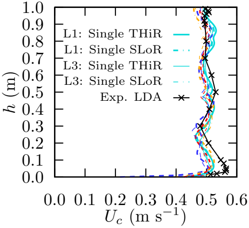
Channel suspension

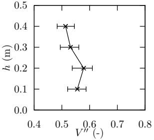
Whole channel simulations

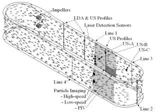
Lines 1 and 3



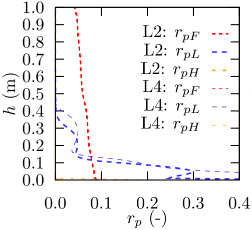


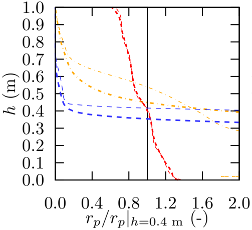


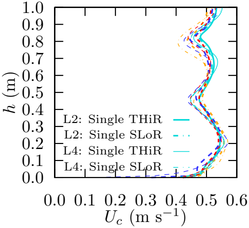




Lines 2 and 4







Channel suspension

Conclusions

- Velocity profiles in the channel influence the transport of the lightest phases around the channel
- Channel section has limited validity due to the uniform velocity profiles
- While simulations of the whole channel can produce similar flow structures
- Lightest agglomerate ($d_p = 0.5$ mm; $\rho_p = 1002$ kg m^{-3}) produces a remarkably good result
- Flow structures on impeller side are generated in or directly after the second bend
- The heavier phases tend to sink
- Nevertheless fibre agglomerates still accumulate on the channel base for all phase definitions

Channel suspension

Further simulations

- Consider a number of phases simultaneously
  - Fibre or very light fibrous clusters
  - Lighter agglomerate phases with settling velocities of 10-30 mm s^{-1}
  - Heavier agglomerate phases with settling velocities of 40-80 mm s^{-1}
  - Fine grains?
- Possible use of alternative turbulence models

Conclusions

- Column Sedimentation: Combined EMM-ASM model applied with initial mass fractions gave the best result
- Channel Sedimentation: Physically agrees with experiments though the agreement is dependent on several factors
- Channel Suspension: Only lightest phase agrees with available experimental data
- Large number of uncertainties

Future Work

- Need to reduce the number of uncertainties
- Analysis of recently performed channel suspension experiments
- Implement and perform simulations
  - channel sedimentation for different closure models
  - channel suspension (determined from the recently performed experiments)

Acknowledgments

- Project partners:
  - Institut für Prozeßtechnik, Prozeßautomatisierung und Meßtechnik Hochschule Zittau/Görlitz
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  - Institut für Sicherheitsforschung Helmholtz-Zentrum Dresden-Rossendorf
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- German Federal Ministry of Economy and Labor Contracts No. 1501270, 1501307, 1501360 and 1501363
- This project is not part of the oversight process and does not intend to deliver safety guidelines

Column sedimentation

Determination of volume and mass fractions for MDK

Agglomerate Phase	Terminal Velocity ($mm\ s^{-1}$)	Density ($kg\ m^{-3}$)	Dry Mass Fraction (-)	Mass Ratio* (-)	Dry Volume Fraction (-)
1	10	1003.48	0.00020‡	0.047*	0.030
2	14	1007.97	0.00009‡	0.021*	0.008
3	20	1015.05	0.00009‡	0.021*	0.005
4	28	1025.80	0.00012‡	0.028*	0.004
5	37	1041.65	0.00026‡	0.063*	0.006
6	48	1064.20	0.00035‡	0.084*	0.005
7	61	1095.30	0.00082‡	0.197*	0.008
8	77	1136.96	0.00098‡	0.237*	0.007
9	94	1191.25	0.00094‡	0.228*	0.005
10†	114	1260.15	0.00030‡	0.072	0.001
Sum	-	-	0.00414	1.000	0.079+

‡ Initial conditions for mass fractions in the ASM case

* Initial conditions for mixture fractions in the EMM-ASM case

+ Volume fraction initial condition for the EMM-ASM case

† Constraint for the EMM-ASM case

Column sedimentation

Determination of volume and mass fractions for MD2

Agglomerate Phase	Terminal Velocity ($mm\ s^{-1}$)	Density ($kg\ m^{-3}$)	Dry Mass Fraction (-)	Mass Ratio* (-)	Dry Volume Fraction (-)
1	10	1003.48	0.00023‡	0.053*	0.0346
2	14	1007.97	0.00032‡	0.074*	0.0289
3	20	1015.05	0.00042‡	0.100*	0.0235
4	28	1025.80	0.00041‡	0.096*	0.0142
5	37	1041.65	0.00058‡	0.137*	0.0131
6	48	1064.20	0.00057‡	0.133*	0.0084
7	61	1095.30	0.00073‡	0.171*	0.0074
8	77	1136.96	0.00065‡	0.153*	0.0047
9	94	1191.25	0.00027‡	0.063*	0.0014
10†	114	1260.15	0.00009‡	0.020	0.0003
Sum	-	-	0.00426	1.000	0.1363+

‡ Initial conditions for mass fractions in the ASM case

* Initial conditions for mixture fractions in the EMM-ASM case

+ Volume fraction initial condition for the EMM-ASM case

† Constraint for the EMM-ASM case

Channel sedimentation

Determination of volume and mass fractions for MDK

Agglomerate Phase	Terminal Velocity ($mm\ s^{-1}$)	Density ($kg\ m^{-3}$)	Dry Mass Fraction (-)	Mass Ratio* (-)	Dry Volume Fraction (-)
1	10	1003.48	0.00098	0.047*	0.150
2	14	1007.97	0.00044	0.021*	0.040
3	20	1015.05	0.00044	0.021*	0.024
4	28	1025.80	0.00059	0.028*	0.020
5	37	1041.65	0.00131	0.063*	0.029
6	48	1064.20	0.00174	0.084*	0.026
7	61	1095.30	0.00407	0.197*	0.041
8	77	1136.96	0.00490	0.237*	0.035
9	94	1191.25	0.00469	0.228*	0.024
10†	114	1260.15	0.00149	0.072	0.006
Sum	-	-	0.02065	1.000	0.397‡

* Mass fraction conditions for mixture fractions

‡ Volume fraction condition

† Constraint for the EMM-ASM

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Channel sedimentation

Determination of volume and mass fractions for MD2

Agglomerate Phase	Terminal Velocity ($mm\ s^{-1}$)	Density ($kg\ m^{-3}$)	Dry Mass Fraction (-)	Mass Ratio* (-)	Dry Volume Fraction (-)
1	10	1003.48	0.00112	0.053*	0.173
2	14	1007.97	0.00159	0.074*	0.144
3	20	1015.05	0.00212	0.100*	0.117
4	28	1025.80	0.00204	0.096*	0.071
5	37	1041.65	0.00292	0.137*	0.065
6	48	1064.20	0.00282	0.133*	0.042
7	61	1095.30	0.00362	0.171*	0.037
8	77	1136.96	0.00326	0.153*	0.023
9	94	1191.25	0.00134	0.063*	0.007
10†	114	1260.15	0.00044	0.020	0.002
Sum	-	-	0.02127	1.000	0.682‡

* Mass fraction conditions for mixture fractions

‡ Volume fraction condition

† Constraint for the EMM-ASM

Uncertainties

Experiments

- Variation agglomerate size, shape, compactness and convexity
- Particle characteristics unknown in the channel suspension experiments
  - previous measurements in a quiescent column
  - how do the fluid interactions affect size, shape, compactness, convexity and density
- Mass of fine grain particles released unknown
  - affects mass of fibre agglomerates transported
  - accounts for up to 30% of agglomerate mass
- Laser detection sensors
  - calibration against the concentration of fibre agglomerates
  - influence of different agglomerates on the signal
  - insufficient number of detectors (top half of the channel and near the base)
  - variation of fibre agglomerate distribution over channel width
- Particle imaging
  - variation of fibre agglomerate distribution over channel width

Uncertainties

Simulations

- Single dispersed phase, with assumed constant agglomerate size, density and shape in channel simulations
- Confirm that fibre agglomerates do not undergo flocculation, erosion and breakage at the defined flow conditions
- High velocity condition should leads to suspension of the fibre agglomerates
  - lower concentrations
  - lower mixture viscosities
  - lower particle-particle collision frequencies and flocculation rates
  - stabilization erosion and breakage (needs experimental confirmation)
- Observed velocities in PWR and BWR are less than 0.2 m s^{-1}, where combined effects are observed
- Fibre inlet velocity condition for the sedimentation simulation needs confirmation
- Grid resolution in the boundary layer is also significant as the channel width is small.
- Finer meshes may cause a vertical shift in the resolved volume fraction profiles.
- Best practice guidelines will be followed
  - once appropriate phase definitions are selected
  - after execution of detailed suspension experimental investigations