Application of multiphase flow modeling techniques to the transport of submerged mineral wool fibers

Gregory Cartland-Glover and Eckhard Krepper

Institut für Sicherheitsforschung

Forschungszentrum Dresden Rossendorf

Sören Alt and Wolfgang Kästner

Institut für Proßtechnik, Prozessautomatisierung und Meßtechnik

IPM HOCHSCHULE ZITTAU/GÖRLITZ

HOCHSCHULE ZITTAU/GÖRLITZ (FH) - University of Applied Sciences

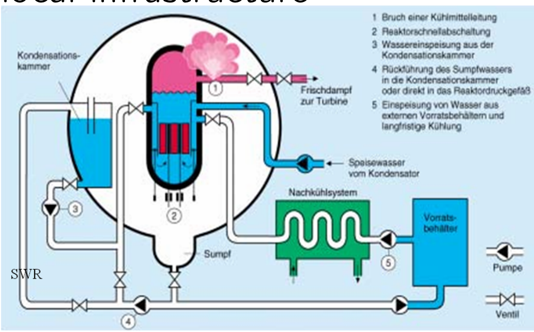
11^{th} July 2007

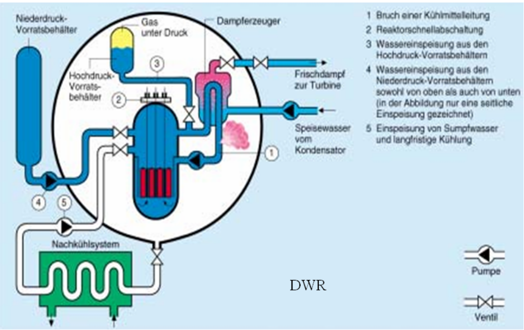
Debris generation and transport in BWR and PWR

- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres

Debris generation and transport in BWR and PWR

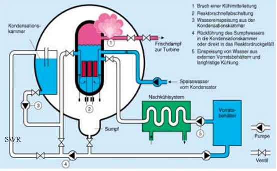
- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres
- Generated by LOCA steam jets destroying insulation material on local infrastructure

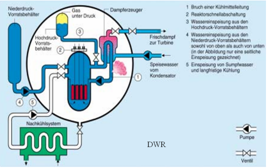




Debris generation and transport in BWR and PWR

- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres
- Generated by LOCA steam jets destroying insulation material on local infrastructure

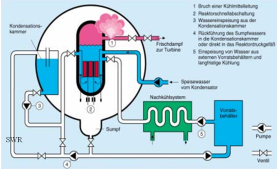


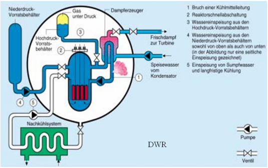


- Transported to the wetwell pool in the containment sump

Debris generation and transport in BWR and PWR

- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres
- Generated by LOCA steam jets destroying insulation material on local infrastructure

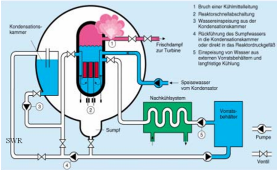


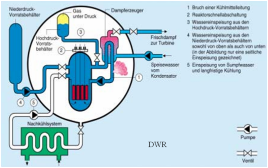


- Transported to the wetwell pool in the containment sump
- Fine particles can remain suspended for several days, whilst heavier particles descend to the base of the sump

Debris generation and transport in BWR and PWR

- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres
- Generated by LOCA steam jets destroying insulation material on local infrastructure

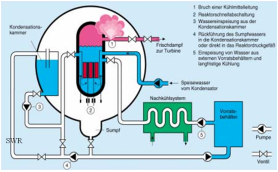


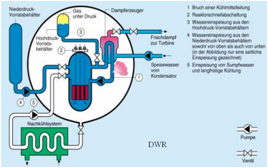


- Transported to the wetwell pool in the containment sump
- Fine particles can remain suspended for several days, whilst heavier particles descend to the base of the sump
- Water jets and recirculation pumps cause wetted fibres and agglomerated particles to be transported to strainers and pumps

Debris generation and transport in BWR and PWR

- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres
- Generated by LOCA steam jets destroying insulation material on local infrastructure

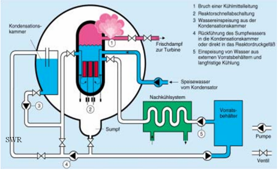


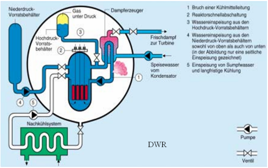


- Transported to the wetwell pool in the containment sump
- Fine particles can remain suspended for several days, whilst heavier particles descend to the base of the sump
- Water jets and recirculation pumps cause wetted fibres and agglomerated particles to be transported to strainers and pumps
- Increases in pressure drop across the strainers can exceed pump specifications

Debris generation and transport in BWR and PWR

- Typical particles include paint chips, metal casings, lost tools and mineral wool fibres
- Generated by LOCA steam jets destroying insulation material on local infrastructure

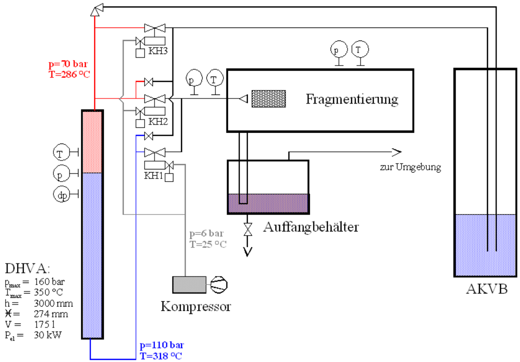




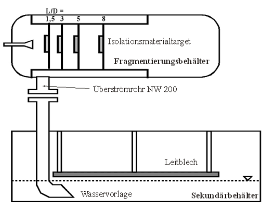
- Transported to the wetwell pool in the containment sump
- Fine particles can remain suspended for several days, whilst heavier particles descend to the base of the sump
- Water jets and recirculation pumps cause wetted fibres and agglomerated particles to be transported to strainers and pumps
- Increases in pressure drop across the strainers can exceed pump specifications
- Can quickly compromise the *defense-in-depth* concept

Project Scope

- Particle debris generation by steam blasting



Fragmentierungsbehälter

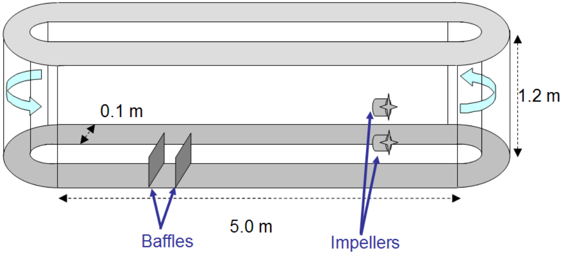


Project Scope

- Particle debris generation by steam blasting
- Terminal velocity and sinking characteristics in a vertical column

Project Scope

- Particle debris generation by steam blasting
- Terminal velocity and sinking characteristics in a vertical column
- Sedimentation and resuspension of submerged particles in a horizontal flow



Project Scope

- Particle debris generation by steam blasting
- Terminal velocity and sinking characteristics in a vertical column
- Sedimentation and resuspension of submerged particles in a horizontal flow
- Pressure drop analysis with the accumulation of particles in filters/strainers

Project Scope

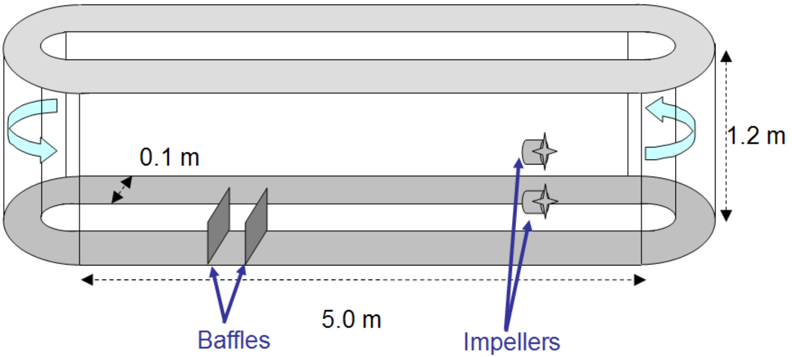
- Particle debris generation by steam blasting
- Terminal velocity and sinking characteristics in a vertical column
- Sedimentation and resuspension of submerged particles in a horizontal flow
- Pressure drop analysis with the accumulation of particles in filters/strainers
- Multiphase water jet injection

Project Scope

- Particle debris generation by steam blasting
- Terminal velocity and sinking characteristics in a vertical column
- Sedimentation and resuspension of submerged particles in a horizontal flow
- Pressure drop analysis with the accumulation of particles in filters/strainers
- Multiphase water jet injection
- Scale-up to containment sump scale with
  + typical geometries
  + multiphase interactions and phenomena
  + equipment (pumps, filters, etc)

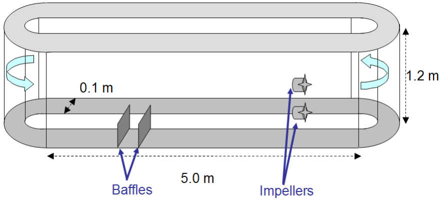
Study of sedimentation and resuspension of submerged particles in a horizontal flow

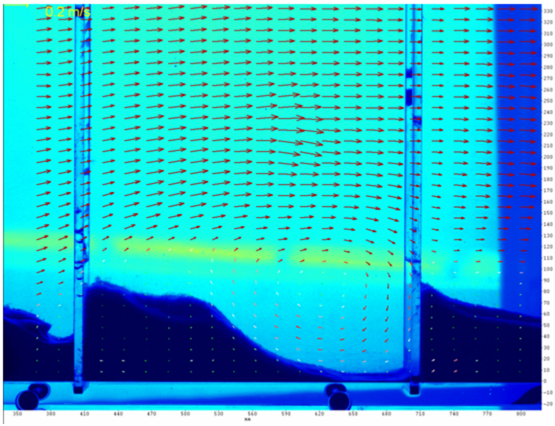
- Experimental study uses



Study of sedimentation and resuspension of submerged particles in a horizontal flow

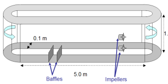
- Experimental study uses
  - Laser PIV
  - High-speed video

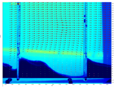


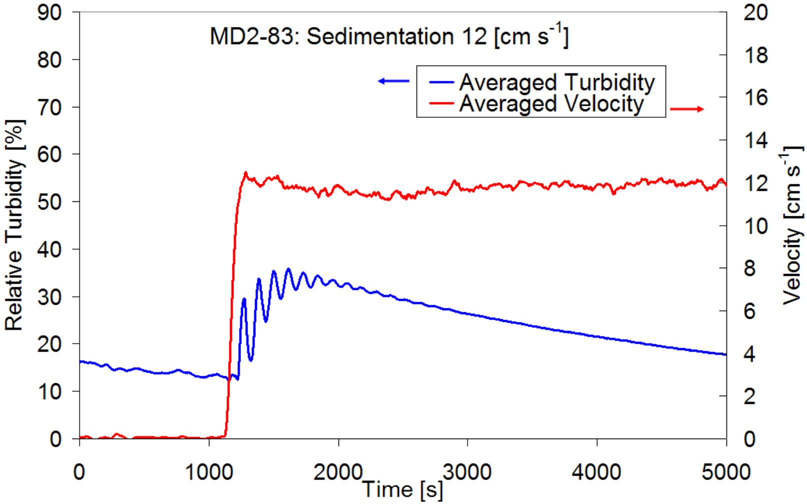


Study of sedimentation and resuspension of submerged particles in a horizontal flow

- Experimental study uses
  - Laser PIV
  - High-speed video
  - Ultrasound velocity
  - Turbidity

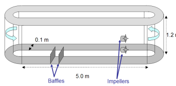


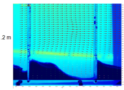


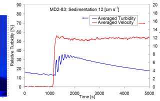


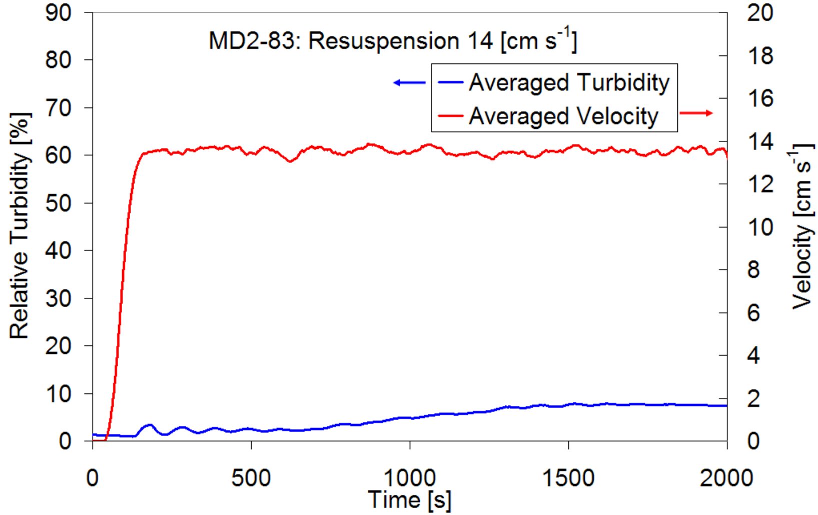
Study of sedimentation and resuspension of submerged particles in a horizontal flow

- Experimental study uses
  - Laser PIV
  - High-speed video
  - Ultrasound velocity
  - Turbidity
  - Pertinent concentrations



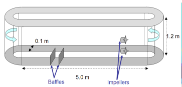


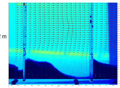


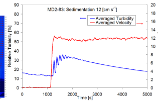


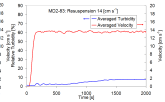
Study of sedimentation and resuspension of submerged particles in a horizontal flow

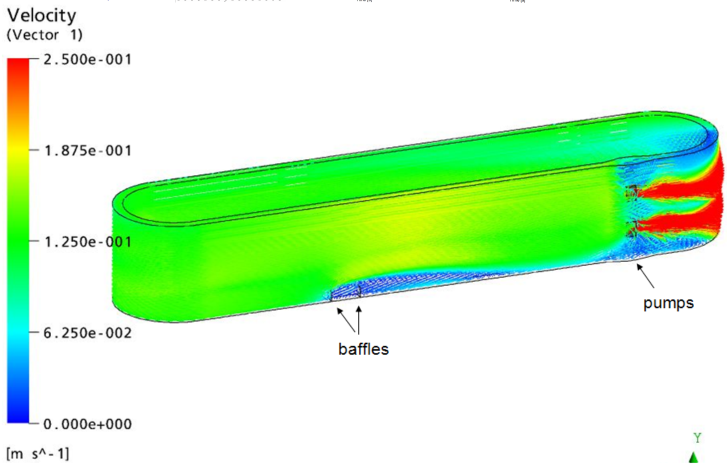
- Experimental study uses
  - Laser PIV
  - High-speed video
  - Ultrasound velocity
  - Turbidity
  - Pertinent concentrations
- Numerical study can examine
  - Whole channel





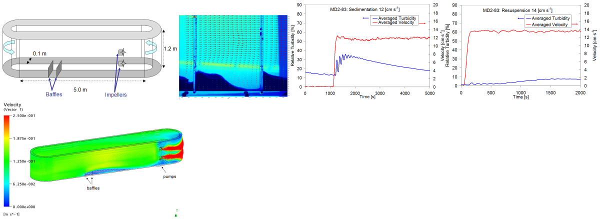


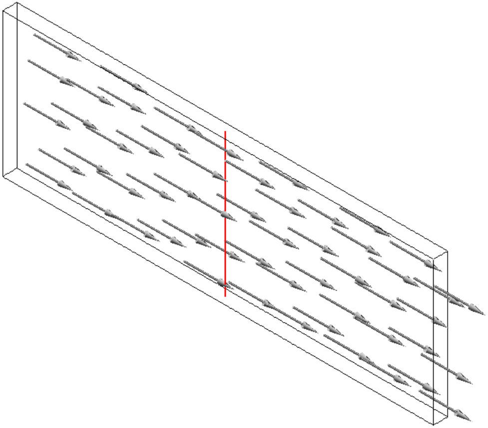




Study of sedimentation and resuspension of submerged particles in a horizontal flow

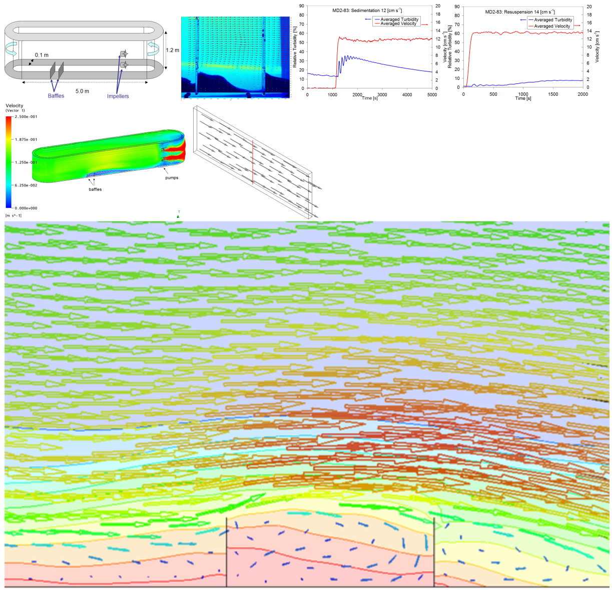
- Experimental study uses
  - Laser PIV
  - High-speed video
  - Ultrasound velocity
  - Turbidity
  - Pertinent concentrations
- Numerical study can examine
  - Whole channel
  - Channel section upstream of the impeller





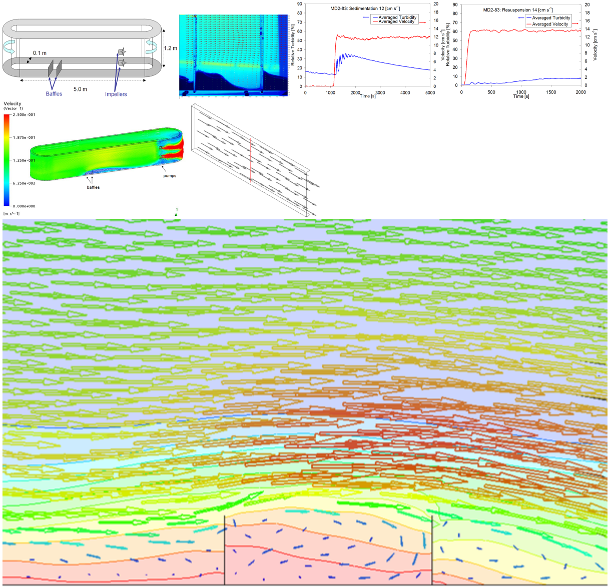
Study of sedimentation and resuspension of submerged particles in a horizontal flow

- Experimental study uses
  - Laser PIV
  - High-speed video
  - Ultrasound velocity
  - Turbidity
  - Pertinent concentrations
- Numerical study can examine
  - Whole channel
  - Channel section upstream of the impeller
  - Flow disruption by baffles



Study of sedimentation and resuspension of submerged particles in a horizontal flow

- Experimental study uses
  - Laser PIV
  - High-speed video
  - Ultrasound velocity
  - Turbidity
  - Pertinent concentrations
- Numerical study can examine
  - Whole channel
  - Channel section upstream of the impeller
  - Flow disruption by baffles
- To determine the impact of
  - Local velocity field
  - Local concentration profiles
  - Viscosity
  - Buoyancy, drag and turbulence dispersion forces



Overview of numerical models used

- Eulerian-Eulerian multiphase flow

Overview of numerical models used

- Eulerian-Eulerian multiphase flow
- SST turbulence

Overview of numerical models used

- Eulerian-Eulerian multiphase flow
- SST turbulence
- Virtual particle (1)

Overview of numerical models used

- Eulerian-Eulerian multiphase flow
- SST turbulence
- Virtual particle (1)
- Viscosity closure models (2) to (7)
  + Relative and mixture (2) and (3)
  + Dispersed phase eddy viscosity (4)
  + Continuous phase eddy viscosity (5) and (6)

Overview of numerical models used

- Eulerian-Eulerian multiphase flow
- SST turbulence
- Virtual particle (1)
- Viscosity closure models (2) to (7)
  - Relative and mixture (2) and (3)
  - Dispersed phase eddy viscosity (4)
  - Continuous phase eddy viscosity (5) and (6)
- Interphase forces (7) to (12)
  - Buoyancy (7)
  - Drag (8)
  - Turbulent Dispersion (9)

Overview of numerical models used

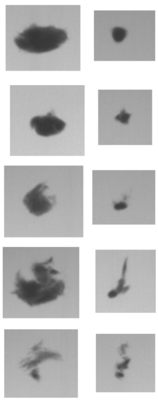
- Eulerian-Eulerian multiphase flow
- SST turbulence
- Virtual particle (1)
- Viscosity closure models (2) to (7)
  - Relative and mixture (2) and (3)
  - Dispersed phase eddy viscosity (4)
  - Continuous phase eddy viscosity (5) and (6)
- Interphase forces (7) to (12)
  - Buoyancy (7)
  - Drag (8)
  - Turbulent Dispersion (9)
- Boundary and initial conditions
  - Low velocity, sedimenting conditions
  - Medium velocity, sedimenting and resuspending conditions
  - High velocity, transport of solids with little sedimentation

The virtual particle

- Particles can be classified by
  - sphericity
  - compactness
  - convexity

Class Particles

1
2
3
4
5



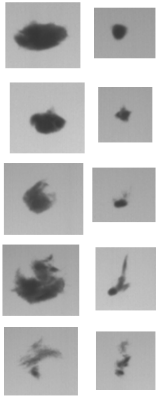
d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

The virtual particle

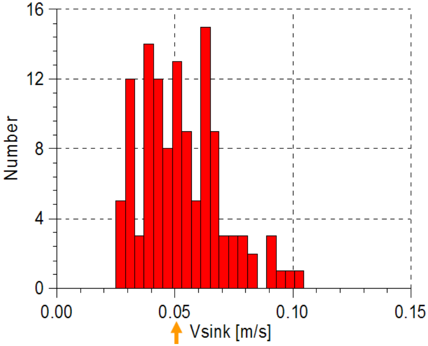
- Particles can be classified by
  - sphericity
  - compactness
  - convexity

Class Particles

1
2
3
4
5



- Measured distribution of agglomerate velocities



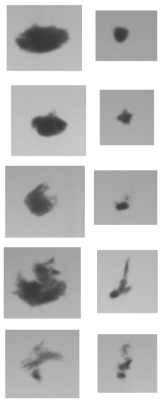
d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

The virtual particle

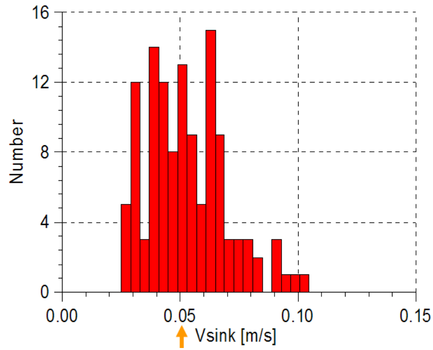
- Particles can be classified by
  - sphericity
  - compactness
  - convexity

Class Particles

1
2
3
4
5



- Measured distribution of agglomerate velocities
- Mean terminal velocity of particles 0.05 m s^{-1}



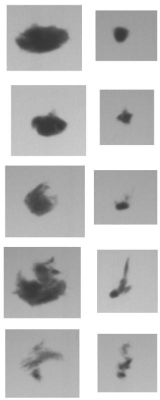
d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

The virtual particle

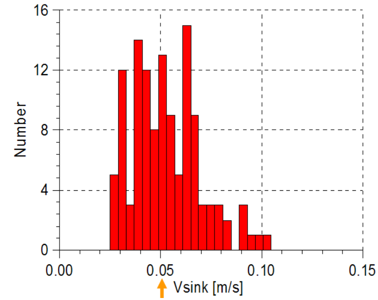
- Particles can be classified by
  - sphericity
  - compactness
  - convexity

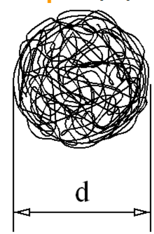
Class Particles

1
2
3
4
5



- Measured distribution of agglomerate velocities
- Mean terminal velocity of particles 0.05 m s^{-1}
- Assumed spherical agglomerate of fibres





d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

The virtual particle

- Particles can be classified by
  - sphericity
  - compactness
  - convexity

Class Particles

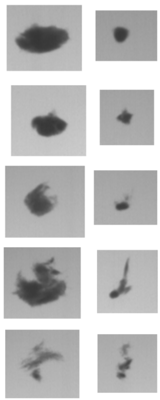
1

2

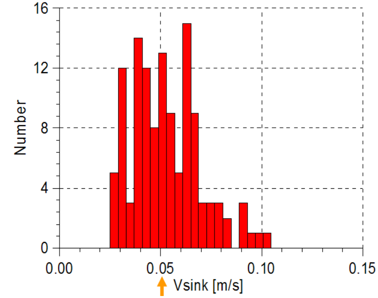
3

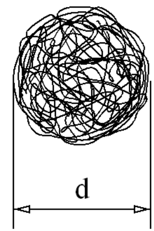
4

5



- Measured distribution of agglomerate velocities
- Mean terminal velocity of particles 0.05 m s^{-1}
- Assumed spherical agglomerate of fibres
- Drag = Buoyancy



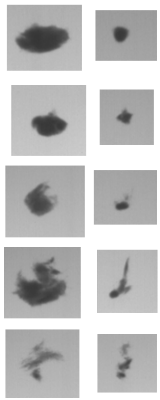


d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

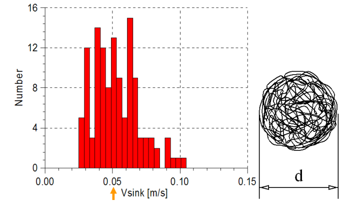
The virtual particle

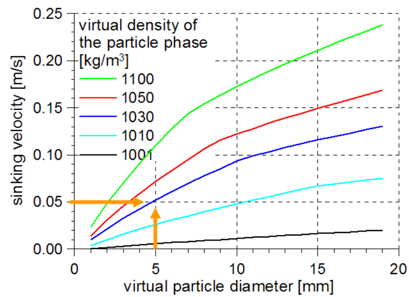
- Particles can be classified by
  - sphericity
  - compactness
  - convexity

Class	Particles
1	
2	
3	
4	
5	



- Measured distribution of agglomerate velocities
- Mean terminal velocity of particles 0.05 m s^{-1}
- Assumed spherical agglomerate of fibres
- Drag = Buoyancy
- Iteratively resolve C_D



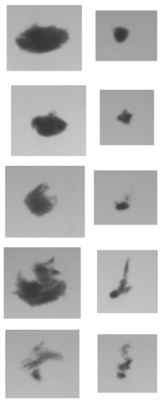


d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

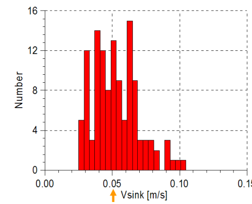
The virtual particle

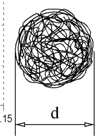
- Particles can be classified by
  - sphericity
  - compactness
  - convexity

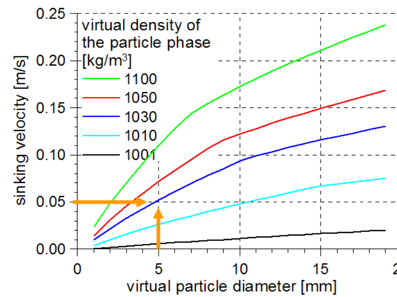
Class	Particles
1	
2	
3	
4	
5	



- Measured distribution of agglomerate velocities
- Mean terminal velocity of particles 0.05 m s^{-1}
- Assumed spherical agglomerate of fibres
- Drag = Buoyancy
- Iteratively resolve C_D
- Terminal velocity $\equiv$ measured mean velocities was obtained
  - $d_p = 5$ mm
  - $\rho_c = 997$ kg m^{-3}
  - $\rho_f = 2800$ kg m^{-3}
  - $\rho_p = 1030$ kg m^{-3}





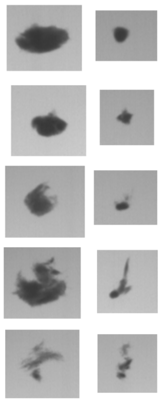


d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

The virtual particle

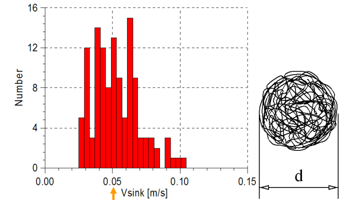
- Particles can be classified by
  - sphericity
  - compactness
  - convexity

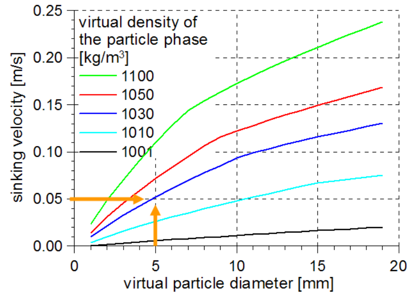
Class	Particles
1	
2	
3	
4	
5	



- Measured distribution of agglomerate velocities
- Mean terminal velocity of particles 0.05 m s^{-1}
- Assumed spherical agglomerate of fibres
- Drag = Buoyancy
- Iteratively resolve C_D
- Terminal velocity ≡ measured mean velocities was obtained
  - $d_p = 5$ mm
  - $\rho_c = 997$ kg m^{-3}
  - $\rho_f = 2800$ kg m^{-3}
  - $\rho_p = 1030$ kg m^{-3}
- This also gives a particle share of 0.018

$$\alpha_p = \frac{\rho_p - \rho_c}{\rho_f - \rho_c} \qquad (1)$$





d = diameter; α = particle share; ρ = density; Subscripts: c = continuous; p = dispersed; f = fibre;

Molecular Viscosities

- Mixture viscosity

$$\mu_{cp} = \mu_c \mu_r \quad (2)$$

C_{hyd} = hydrodynamic constant = 6.2; r = volume fraction; μ = dynamic viscosity; μ_{in} = intrinsic viscosity = 2.5; Subscripts: c = continuous; cp = mixture; r = relative; p = dispersed; pmax = maximum dispersed phase fraction;

Molecular Viscosities

- Mixture viscosity

$$\mu_{cp} = \mu_c \mu_r \tag{2}$$

- Relative viscosity

$$\mu_{r1} = 1 + \begin{cases} 0 & r_p < 0.6 \\ r_p^3 10^4 & r_p \geq 0.6 \end{cases} \tag{3a}$$

$$\mu_{r2} = \left(1 - \frac{r_p}{r_{p\,\max}}\right)^{-\mu_{in} r_{p\,\max}} \tag{3b}$$

$$\mu_{r3} = 1 + \mu_{in} r_p + C_{hyd} r_p^2 \tag{3c}$$

C_{hyd} = hydrodynamic constant = 6.2; r = volume fraction; μ = dynamic viscosity; μ_{in} = intrinsic viscosity = 2.5; Subscripts: c = continuous; cp = mixture; r = relative; p = dispersed; pmax = maximum dispersed phase fraction;

Eddy Viscosities

- Dispersed phase eddy viscosity, where $\nu = \mu/\rho$

$$\nu_{tp} = \frac{\nu_{tc}}{\sigma_{tc}} \tag{4}$$

C_μ = turbulence constant = 0.09; $f_{\max}$ = maximum function; k = turbulent kinetic energy; U = mean velocity vector component; x = position vector component; y = distance to nearest wall; ε = eddy dissipation rate; ν = kinematic viscosity; σ = turbulent Prandtl number; τ = shear rate tensor; ω = eddy frequency; Subscripts: c = continuous; i = ith direction vector component; j = jth direction vector component; p = dispersed; t = turbulent eddy;

Eddy Viscosities

- Dispersed phase eddy viscosity, where $\nu = \mu/\rho$

$$\nu_{tp} = \frac{\nu_{tc}}{\sigma_{tc}} \quad (4)$$

- Continuous phase eddy viscosity

$$\nu_{tc} = c_\mu \frac{k_c^2}{\varepsilon_c} \quad (5a)$$

$$\nu_{tc} = \frac{c_\mu^{0.5} k_c}{f_{\max}\left(c_\mu^{0.5}\omega_c, 2\tau_{ij}\tanh\left[f_{\max}\left(\frac{2k_c^{0.5}}{c_\mu \omega_c y}, \frac{500\nu_c}{y^2\omega_c}\right)^2\right]\right)} \quad (5b)$$

$$\tau_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \quad (6)$$

C_μ = turbulence constant = 0.09; $f_{\max}$ = maximum function; k = turbulent kinetic energy; U = mean velocity vector component; x = position vector component; y = distance to nearest wall; ε = eddy dissipation rate; ν = kinematic viscosity; σ = turbulent Prandtl number; τ = shear rate tensor; ω = eddy frequency; Subscripts: c = continuous; i = i^{th} direction vector component; j = j^{th} direction vector component; p = dispersed; t = turbulent eddy;

Interphase forces

- Buoyancy force characterises the motion of the particles

$$S_{cp}^{B} = \mathbf{g} r_p \left(\rho_p - \rho_c \right) \quad (7)$$

C_{cp}^{D} = momentum exchange coefficient; C_{TD} = turbulence dispersion coefficient; $\mathbf{g}$ = gravitational acceleration; M = interfacial force; r = volume fraction; S = body or external force; $\mathbf{U}$ = mean velocity vector; ν = kinematic viscosity; ρ = density; σ = turbulent Prandtl number; Subscripts: c = continuous; cp = mixture; p = dispersed; t = turbulent eddy; Superscripts: B = buoyancy; D = drag; TD = turbulence dispersion

Interphase forces

- Buoyancy force characterises the motion of the particles

$$S_{cp}^{B} = \mathbf{g} r_p \left(\rho_p - \rho_c\right) \quad (7)$$

- Drag Force characterises the resistance of the particles to fluid flow

$$M_{cp}^{D} = C_{cp}^{D} \left(\mathbf{U}_p - \mathbf{U}_c\right) \quad (8)$$

C_{cp}^{D} = momentum exchange coefficient; C_{TD} = turbulence dispersion coefficient; $\mathbf{g}$ = gravitational acceleration; M = interfacial force; r = volume fraction; S = body or external force; $\mathbf{U}$ = mean velocity vector; ν = kinematic viscosity; ρ = density; σ = turbulent Prandtl number; Subscripts: c = continuous; cp = mixture; p = dispersed; t = turbulent eddy; Superscripts: B = buoyancy; D = drag; TD = turbulence dispersion

Interphase forces

- Buoyancy force characterises the motion of the particles

$$S_{cp}^{B} = \mathbf{g} r_p \left(\rho_p - \rho_c\right) \tag{7}$$

- Drag Force characterises the resistance of the particles to fluid flow

$$M_{cp}^{D} = C_{cp}^{D} \left(\mathbf{U}_p - \mathbf{U}_c\right) \tag{8}$$

- Turbulent dispersion force characterises the response and spread of particles due to turbulent eddies

$$M_{cp}^{TD} = C_{TD} C_{cp}^{D} \frac{\nu_{tc}}{\sigma_{tc}} \left(\frac{\nabla r_p}{r_p} - \frac{\nabla r_c}{r_c}\right) \tag{9}$$

C_{cp}^{D} = momentum exchange coefficient; C_{TD} = turbulence dispersion coefficient; $\mathbf{g}$ = gravitational acceleration; M = interfacial force; r = volume fraction; S = body or external force; $\mathbf{U}$ = mean velocity vector; ν = kinematic viscosity; ρ = density; σ = turbulent Prandtl number; Subscripts: c = continuous; cp = mixture; p = dispersed; t = turbulent eddy; Superscripts: B = buoyancy; D = drag; TD = turbulence dispersion

Key terms in drag and turbulent dispersion forces

- Eddy diffusivity hypothesis resolves the spread of volume fraction by velocity fluctuations

$$\overline{r'_k \mathbf{u}'_k} = \frac{\nu_{tk}}{\sigma_{tk}} \nabla \overline{r_k} \quad (10)$$

C_D = drag coefficient; d = particle diameter; Re = Reynolds number; r = volume fraction; r' = fluctuating volume fraction; $\mathbf{U}$ = mean velocity vector; $\mathbf{u}'$ = fluctuating velocity vector; ν = kinematic viscosity; ρ = density; σ = turbulent Prandtl number; Subscripts: c = continuous; cp = mixture; p = dispersed; t = turbulent eddy; T = terminal settling velocity

Key terms in drag and turbulent dispersion forces

- Eddy diffusivity hypothesis resolves the spread of volume fraction by velocity fluctuations

$$\overline{r_k' \mathbf{u}_k'} = \frac{\nu_{tk}}{\sigma_{tk}} \nabla \overline{r_k} \tag{10}$$

- Analogous to eddy viscosity hypothesis

$$\overline{\mathbf{u}_k' \mathbf{u}_k'} = \nu_{tk} \nabla \overline{\mathbf{u}_k} \tag{11}$$

C_D = drag coefficient; d = particle diameter; Re = Reynolds number; r = volume fraction; r' = fluctuating volume fraction; $\mathbf{U}$ = mean velocity vector; $\mathbf{u}'$ = fluctuating velocity vector; ν = kinematic viscosity; ρ = density; σ = turbulent Prandtl number; Subscripts: c = continuous; cp = mixture; p = dispersed; t = turbulent eddy; T = terminal settling velocity

Key terms in drag and turbulent dispersion forces

- Eddy diffusivity hypothesis resolves the spread of volume fraction by velocity fluctuations

$$\overline{r'_k \mathbf{u}'_k} = \frac{\nu_{tk}}{\sigma_{tk}} \nabla \overline{r_k} \tag{10}$$

- Analogous to eddy viscosity hypothesis

$$\overline{\mathbf{u}'_k \mathbf{u}'_k} = \nu_{tk} \nabla \overline{\mathbf{u}_k} \tag{11}$$

- C^D_{cp} = momentum exchange coefficient

$$C^D_{cp} = \frac{3}{4}\frac{C_D}{d_p} r_p \rho_c \left|\mathbf{U}_p - \mathbf{U}_c\right| \tag{12a}$$

$$C_D = \begin{cases} \frac{24}{Re_p} & Re_p \ll 1 \\ \frac{24}{Re_p}\left(1 + 0.15 Re_p^{0.687}\right) & 1 < Re_p < 10^3 \\ 0.44 & 10^3 < Re_p < 2 * 10^5 \end{cases} \tag{12b}$$

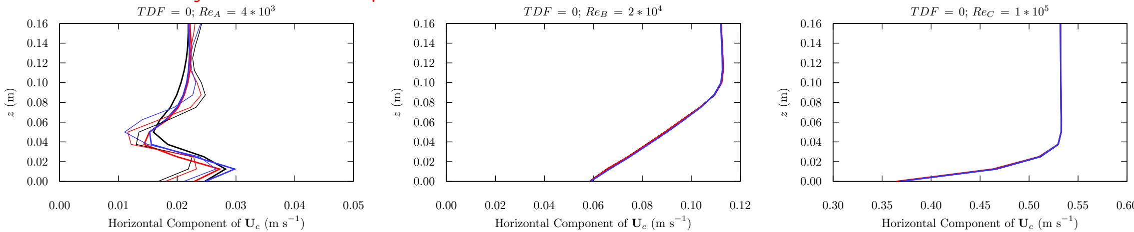
$$Re_p = \frac{d_p U_{np}}{\nu_c} \tag{12c}$$

$$\mathbf{U}_{Tp} = \sqrt{\frac{4}{3}\mathbf{g}\frac{\rho_p - \rho_c}{\rho_c} d_p \frac{1}{C_D}} \tag{12d}$$

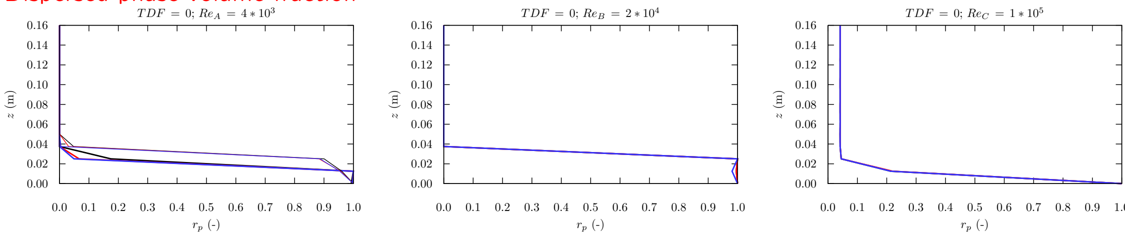
C_D = drag coefficient; d = particle diameter; Re = Reynolds number; r = volume fraction; r' = fluctuating volume fraction; $\mathbf{U}$ = mean velocity vector; $\mathbf{u}'$ = fluctuating velocity vector; ν = kinematic viscosity; ρ = density; σ = turbulent Prandtl number; Subscripts: c = continuous; cp = mixture; p = dispersed; t = turbulent eddy; T = terminal settling velocity

Effect of relative viscosity

Horizontal velocity of continuous phase



Dispersed phase volume fraction

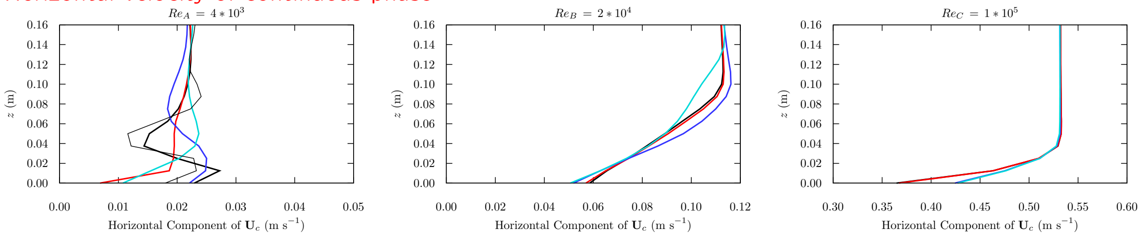


- SST Turbulence: thick solid lines; Laminar: thin solid lines;
- Relative viscosities:

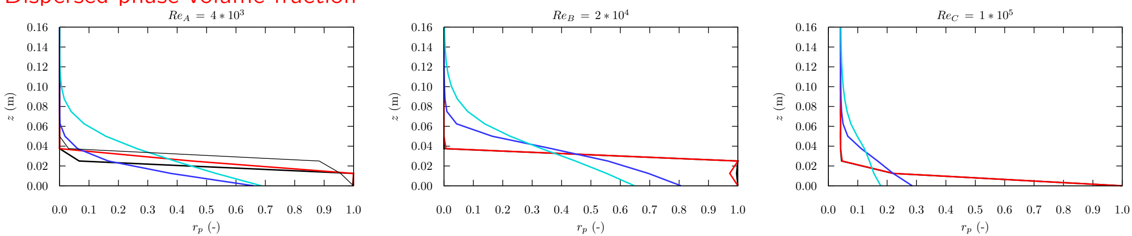
Red : $\mu_{r1} = 1 + \begin{cases} 0 & r_p < 0.6 \\ r_p^3 10^4 & r_p \geq 0.6 \end{cases}$; Blue : $\mu_{r2} = \left(1 - \frac{r_p}{r_{p\,max}}\right)^{-\mu_{in} r_{p\,max}}$; Black: $\mu_{r3} = 1 + \mu_{in} r_p + C_{hyd} r_p^2$;

Effect of coefficient of turbulence dispersion (1)

Horizontal velocity of continuous phase



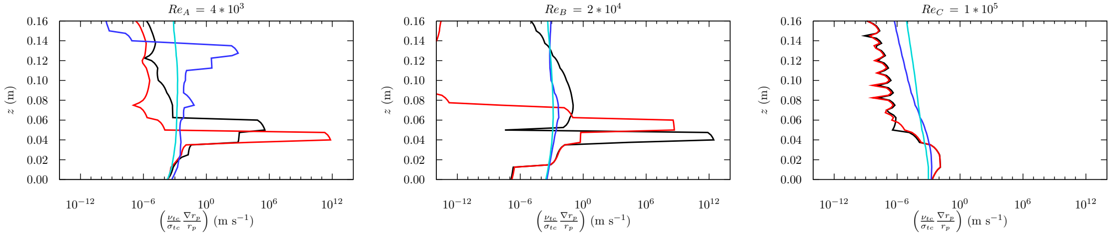
Dispersed phase volume fraction



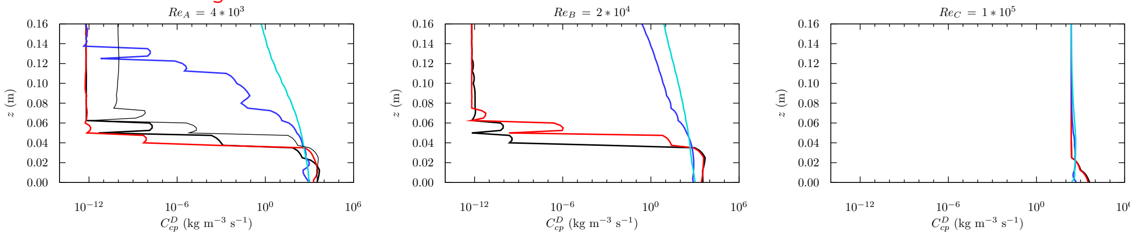
- Coefficient of turbulent dispersion: TDF = 0: thick black solid lines; TDF = 1: thick red lines; TDF = 50: thick blue solid lines; TDF = 100: thick cyan solid lines; Laminar: thin black solid lines;
- Relative viscosity: $\mu_{r2} = \left(1 - \frac{r_p}{r_{p\,\max}}\right)^{-\mu_{in} r_{p\,\max}}$;

Effect of coefficient of turbulence dispersion (2)

Product of eddy diffusivity and volume fraction gradient



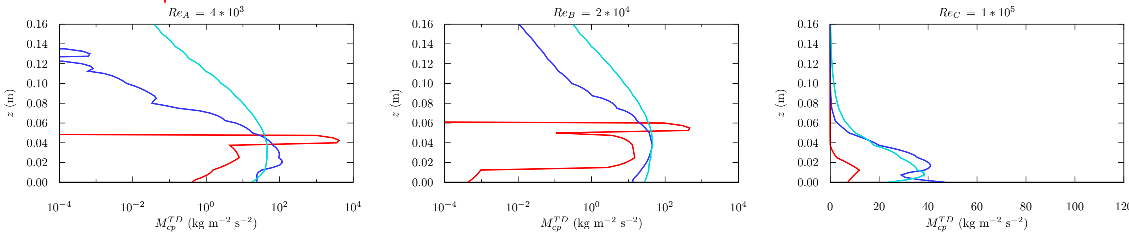
Momentum exchange coefficient



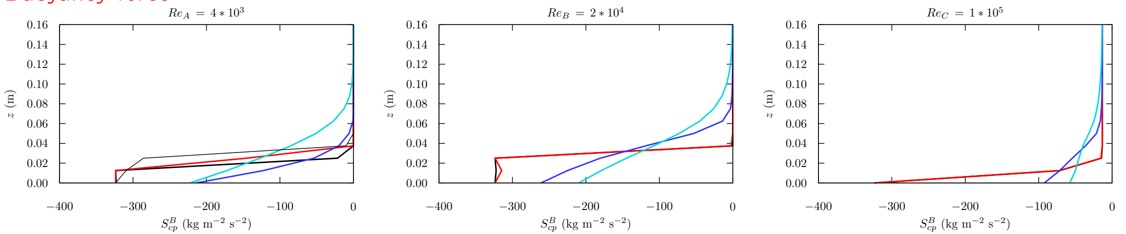
- Coefficient of turbulent dispersion: TDF = 0: thick black solid lines; TDF = 1: thick red lines; TDF = 50: thick blue solid lines; TDF = 100: thick cyan solid lines; Laminar: thin black solid lines;
- Relative viscosity: $\mu_{r2} = \left(1 - \frac{r_p}{r_{p\,\max}}\right)^{-\mu_{in} r_{p\,\max}}$;

Effect of coefficient of turbulence dispersion (3)

Turbulence dispersion force



Buoyancy force



- Coefficient of turbulent dispersion: TDF = 0: thick black solid lines; TDF = 1: thick red lines; TDF = 50: thick blue solid lines; TDF = 100: thick cyan solid lines; Laminar: thin black solid lines;
- Relative viscosity: $\mu_{r2} = \left(1 - \frac{r_p}{r_{p\,max}}\right)^{-\mu_{in} r_{p\,max}}$;

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions
- Selected relative viscosity correlations show no significant effects

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions
- Selected relative viscosity correlations show no significant effects
- Requires a modified turbulent dispersion force to give qualitative phenomena

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions
- Selected relative viscosity correlations show no significant effects
- Requires a modified turbulent dispersion force to give qualitative phenomena
- Modification made through C_{TD}

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions
- Selected relative viscosity correlations show no significant effects
- Requires a modified turbulent dispersion force to give qualitative phenomena
- Modification made through C_{TD}
- Influence of momentum exchange on the turbulence dispersion force is shown at higher velocities

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions
- Selected relative viscosity correlations show no significant effects
- Requires a modified turbulent dispersion force to give qualitative phenomena
- Modification made through C_{TD}
- Influence of momentum exchange on the turbulence dispersion force is shown at higher velocities
- Influence of viscosity is strongest in the particulate layer at lower velocities

Conclusions

- Qualitatively correct phenomena observed at different velocity conditions
- Selected relative viscosity correlations show no significant effects
- Requires a modified turbulent dispersion force to give qualitative phenomena
- Modification made through C_{TD}
- Influence of momentum exchange on the turbulence dispersion force is shown at higher velocities
- Influence of viscosity is strongest in the particulate layer at lower velocities
- Direct experiments to gain further information on the transport properties of the particles

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models
- Use higher velocities to measure turbulence dispersion force

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models
- Use higher velocities to measure turbulence dispersion force
- To resolve the momentum exchange term
  - Particle description
  - Particle drag coefficient
  - Particle contact area

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models
- Use higher velocities to measure turbulence dispersion force
- To resolve the momentum exchange term
  - Particle description
  - Particle drag coefficient
  - Particle contact area
- Relative viscosity has an influence at lower velocities and higher volume fractions
  - Particle shape and orientation
  - Intrinsic viscosity
  - Volume fraction dependency

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models
- Use higher velocities to measure turbulence dispersion force
- To resolve the momentum exchange term
  - Particle description
  - Particle drag coefficient
  - Particle contact area
- Relative viscosity has an influence at lower velocities and higher volume fractions
  - Particle shape and orientation
  - Intrinsic viscosity
  - Volume fraction dependency
- Modify flow by introducing baffles

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models
- Use higher velocities to measure turbulence dispersion force
- To resolve the momentum exchange term
  + Particle description
  + Particle drag coefficient
  + Particle contact area
- Relative viscosity has an influence at lower velocities and higher volume fractions
  + Particle shape and orientation
  + Intrinsic viscosity
  + Volume fraction dependency
- Modify flow by introducing baffles
- Scale-up to containment vessel size

Future Work

- Acquire experimental data to select and validate applied closure and interfacial force models
- Use higher velocities to measure turbulence dispersion force
- To resolve the momentum exchange term
  - Particle description
  - Particle drag coefficient
  - Particle contact area
- Relative viscosity has an influence at lower velocities and higher volume fractions
  - Particle shape and orientation
  - Intrinsic viscosity
  - Volume fraction dependency
- Modify flow by introducing baffles
- Scale-up to containment vessel size
- Increase complexity
  - Particle size and shape distributions
  - Agglomeration and fragmentation models
  - Multiphase interactions (gas-liquid-solid) with descending hot water jets

Acknowledgments

- Project partners:
  - IPM Zittau
    Thoralf Gocht, Rainer Hampel, Alexander Kratzsch, Stefan Renger, Andre Seeliger and *Frank Zacharias*
  - FZD
    Alexander Grahn
- German Federal Ministry of Economy and Labor Contracts No. 1501270 and 1501307