Hydrodynamic Modeling of Mineral Wool Fiber Suspensions in a Two-Dimensional Channel Flow

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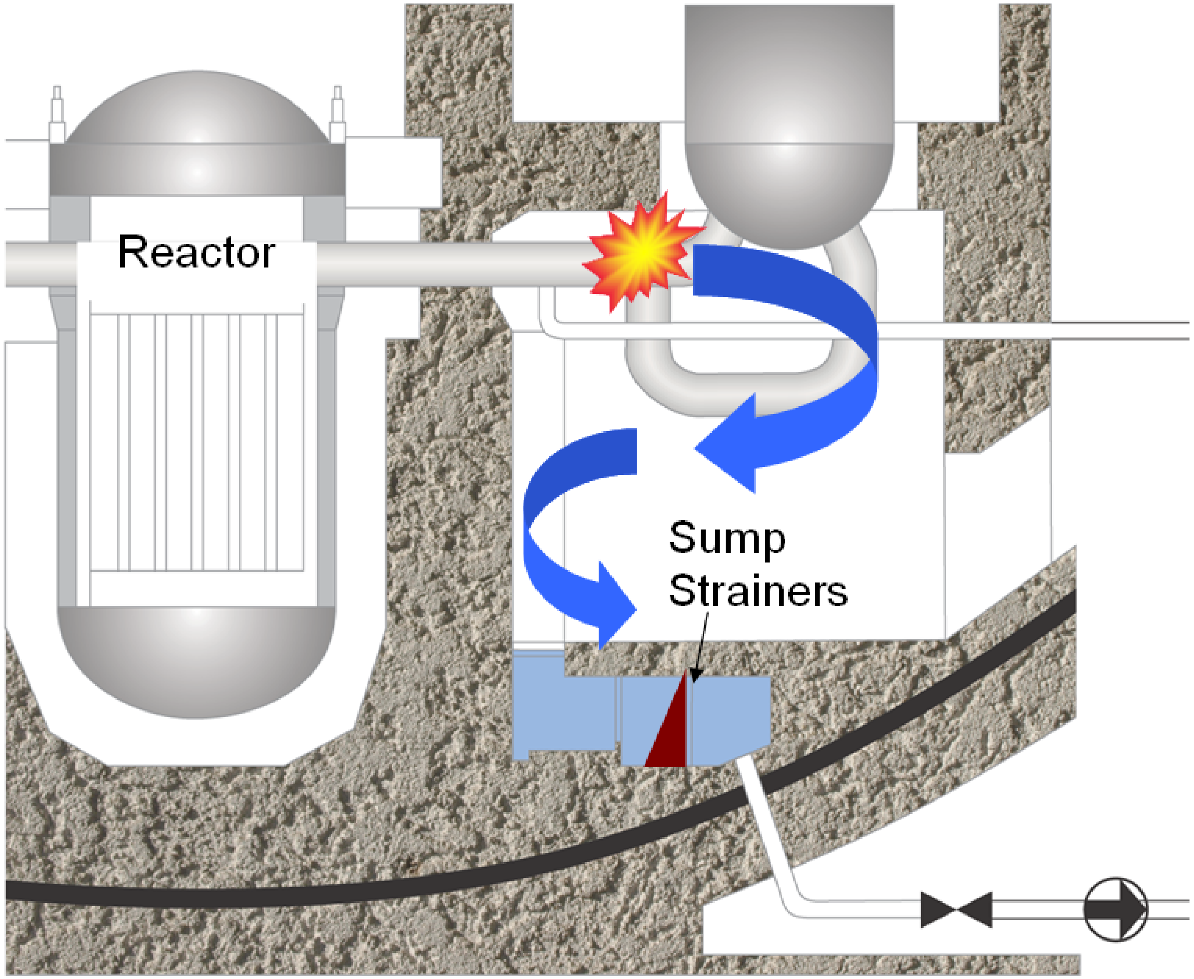
Investigation of the behavior of insulation material in emergency coolant flow

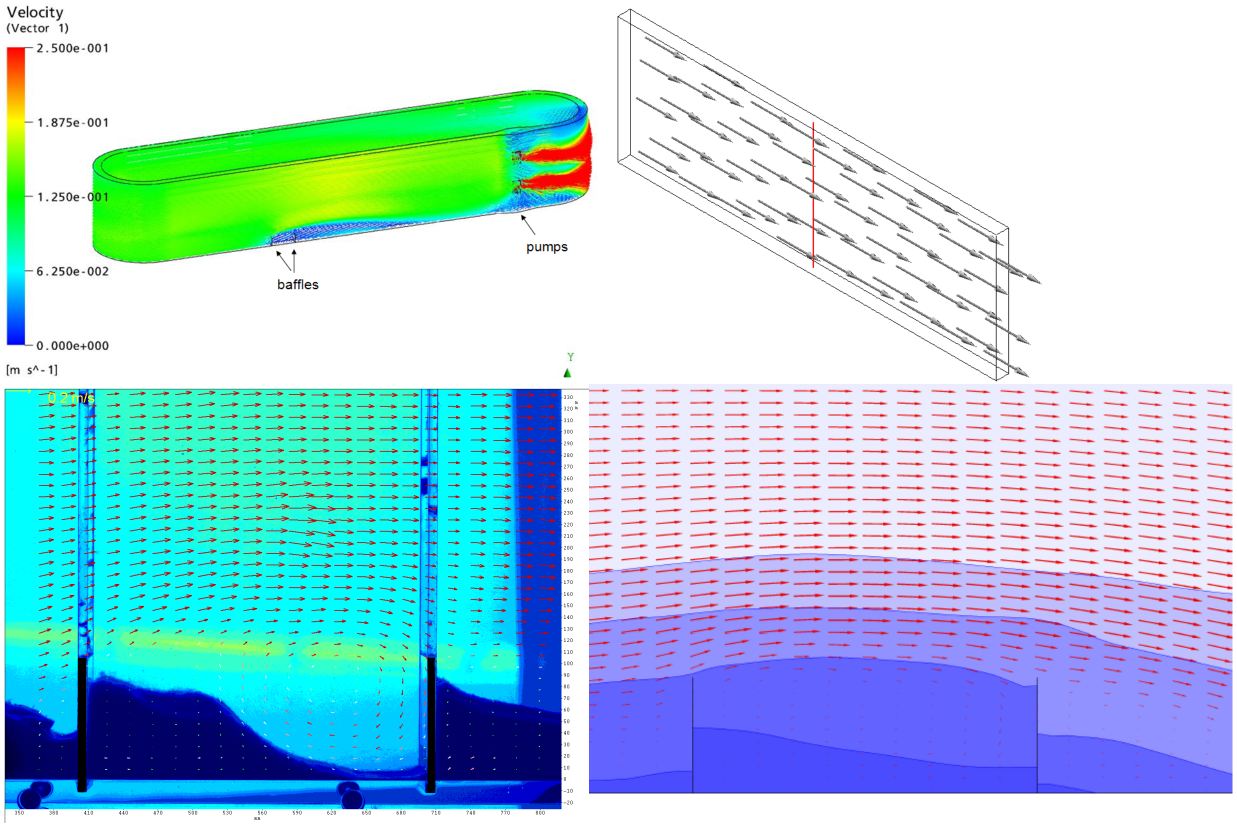
- **The problem**
  - Line break LOCAs
  - Isolation material or other debris is released
  - Some debris is transported through to the containment sump
  - At the sump strainers
    - Fine debris can penetrate the strainer
    - Large debris is deposited
  - The consequences
    - Pressure drop increases could compromise the ECC pump
    - Fibres can accumulate in the reactor core
- **Combined experimental and numerical study is being performed on mineral wool fiber agglomerate generation, transport and accumulation**



Thanks to TUEV Sued for use of the image.

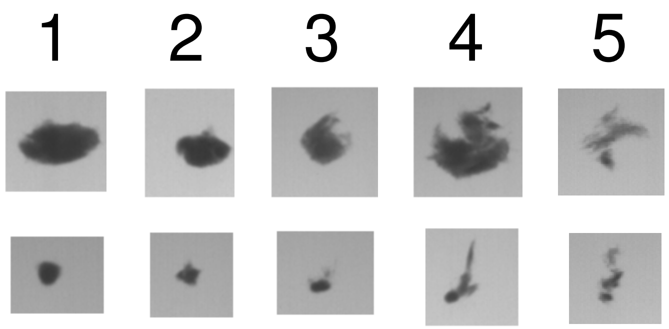
Studies of the horizontal transport of submerged mineral wool fibers

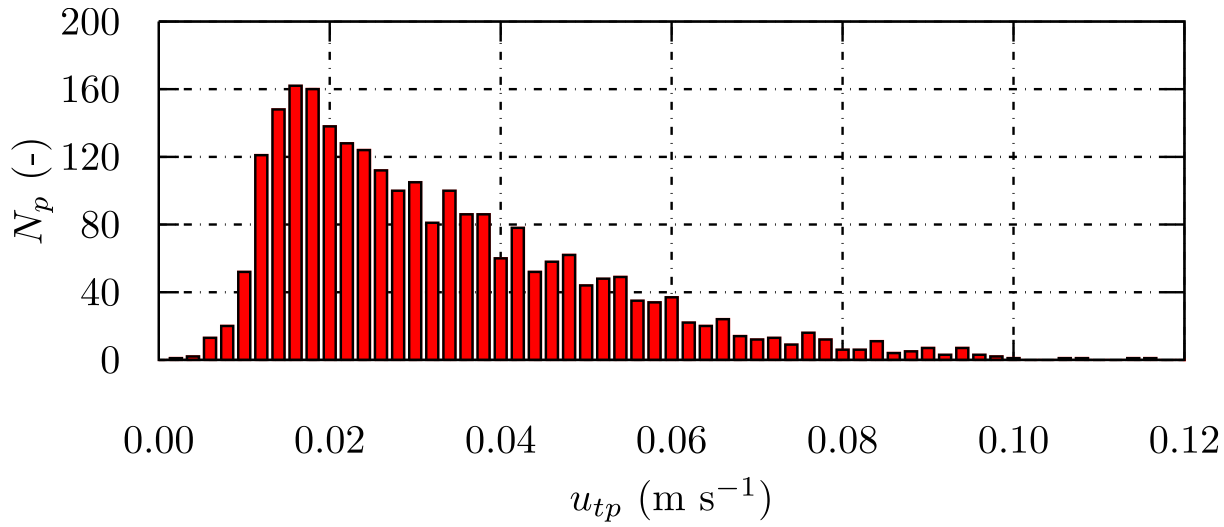
- Numerical models
  - Eulerian-Eulerian multiphase flow
  - Dispersed fluid form
  - SST turbulence with automatic wall functions
- Boundary and initial conditions
  - Section or whole of the channel
  - Velocity inlet and outlet conditions ($Re \sim 10.4 * 10^4$ or 0.5 m s^{-1})
  - Uniform volume fraction of dispersed phase at the inlet
  - Medium turbulence intensity
  - Total fiber mass of $\sim$ 440g
- To determine the impact of
  - Phase description
  - Local velocity and turbulence field
  - Local concentration profiles
  - Viscosity
  - Buoyancy, drag and turbulence dispersion forces

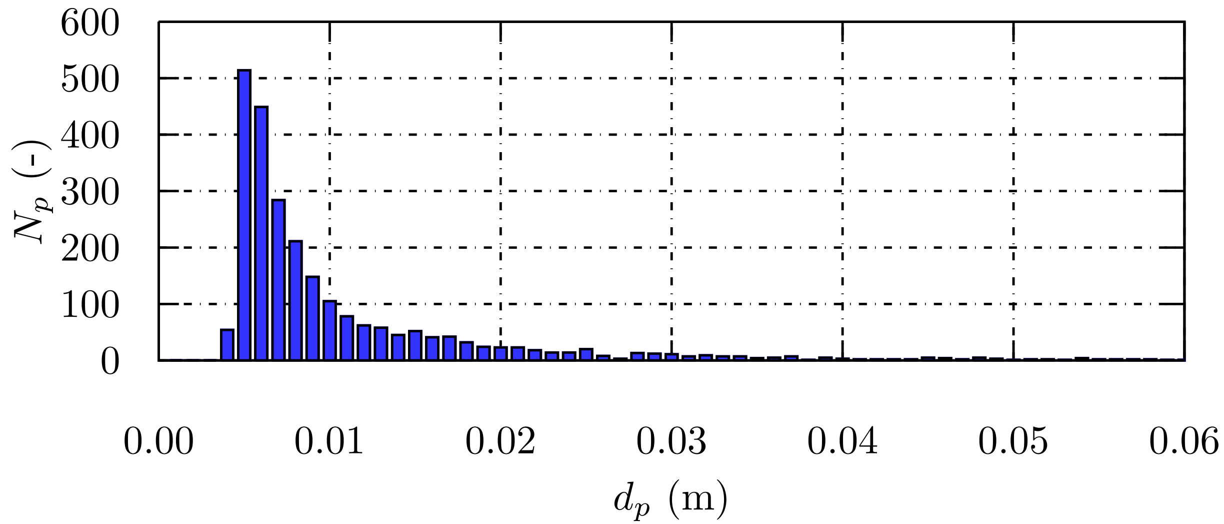


Categorisation of the dispersed phase

Particle Classes





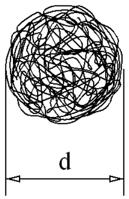


- Particles can be classified by
  - sphericity
  - compactness
  - convexity
- Measured distribution of agglomerate velocities
- Estimated distribution of spherical diameter based on the measured cross-sectional areas of the agglomerates

d_p = particle diameter; N_p = Number of agglomerates; u_{tp} = terminal settling velocity

Dispersed phase morphology

- Assumed spherical agglomerate of wetted fibers



- Knowing both d_p and u_{tp}, ρ_p can be determined
- Share of fibers and water in the virtual particle

$$\zeta_p = \frac{\rho_p - \rho_c}{\rho_f - \rho_c}$$

- Viscosity
  - Mixture viscosity

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

  - Relative viscosity

$$\mu_r = 1 + 2.5 r_p + 7.6 r_p^2 \qquad \text{(Batchelor, 1977)}$$

r = volume fraction; μ = dynamic viscosity; ρ = density; ζ = fiber share; Subscripts: c = continuous; cp = mixture; f = individual fiber; r = relative; p = dispersed;

Interphase Forces

- Buoyancy force characterises the motion of the particles

$$\vec{S}^{B}_{cp} = \vec{g} r_p \left(\rho_p - \rho_c\right)$$

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

$$\vec{M}^{D}_{cp} = C^{D}_{cp} \left(\vec{u}_p - \vec{u}_c\right)$$

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

$$\vec{M}^{TD}_{cp} = C_{TD} C^{D}_{cp} \frac{\nu_{tc}}{\sigma_{tc}} \left(\frac{\nabla r_p}{r_p} - \frac{\nabla r_c}{r_c}\right)$$

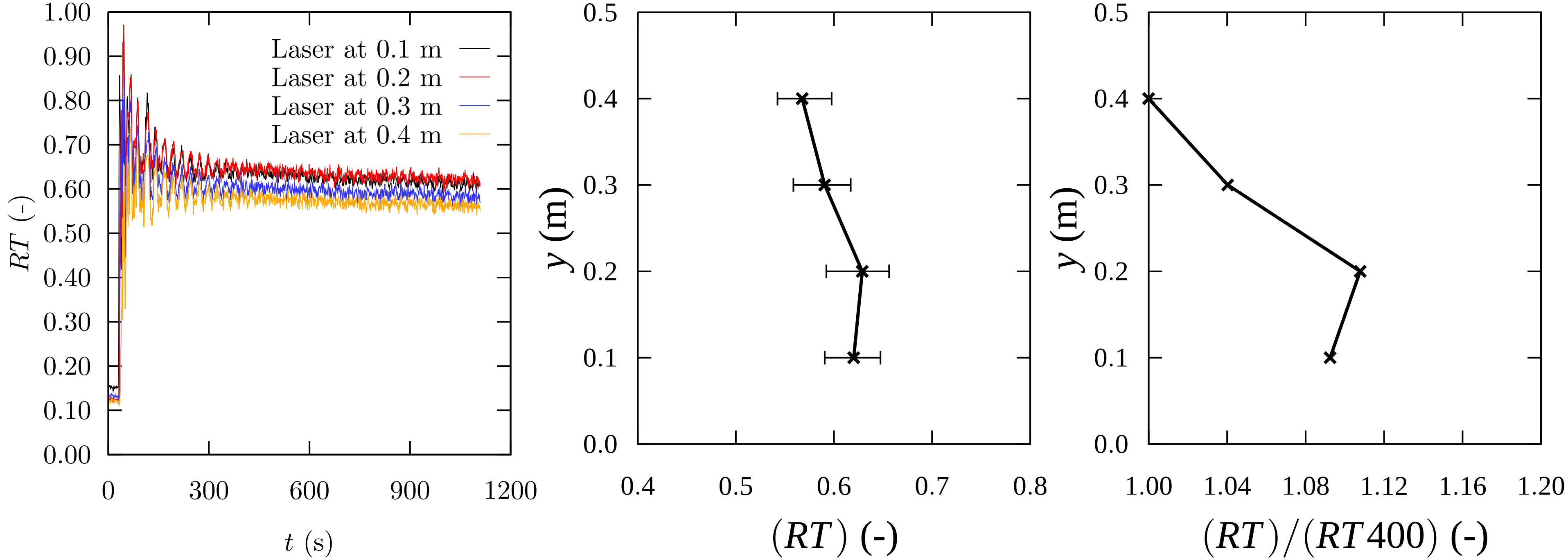
- Momentum exchange coefficient using Schiller-Naumann coefficient

$$C^{D}_{cp} = \frac{3}{4} \frac{C_{D,SN}}{d_p} r_p \rho_c \left|\vec{u}_p - \vec{u}_c\right|$$

C^{D}_{cp} = momentum exchange coefficient; $C_{D,SN}$ = Schiller-Naumann drag coefficient; d_p = particle diameter; C_{TD} = turbulence dispersion coefficient; $\vec{g}$ = gravitational acceleration; $\vec{M}$ = interfacial force; r = volume fraction; $\vec{S}$ = body or external force; $\vec{u}$ = mean velocity vector; ν_{tc} = kinematic turbulent viscosity; ρ = density; σ_{tc} = turbulent Prandtl number; Superscripts: B = buoyancy; D = drag; TD = turbulence dispersion

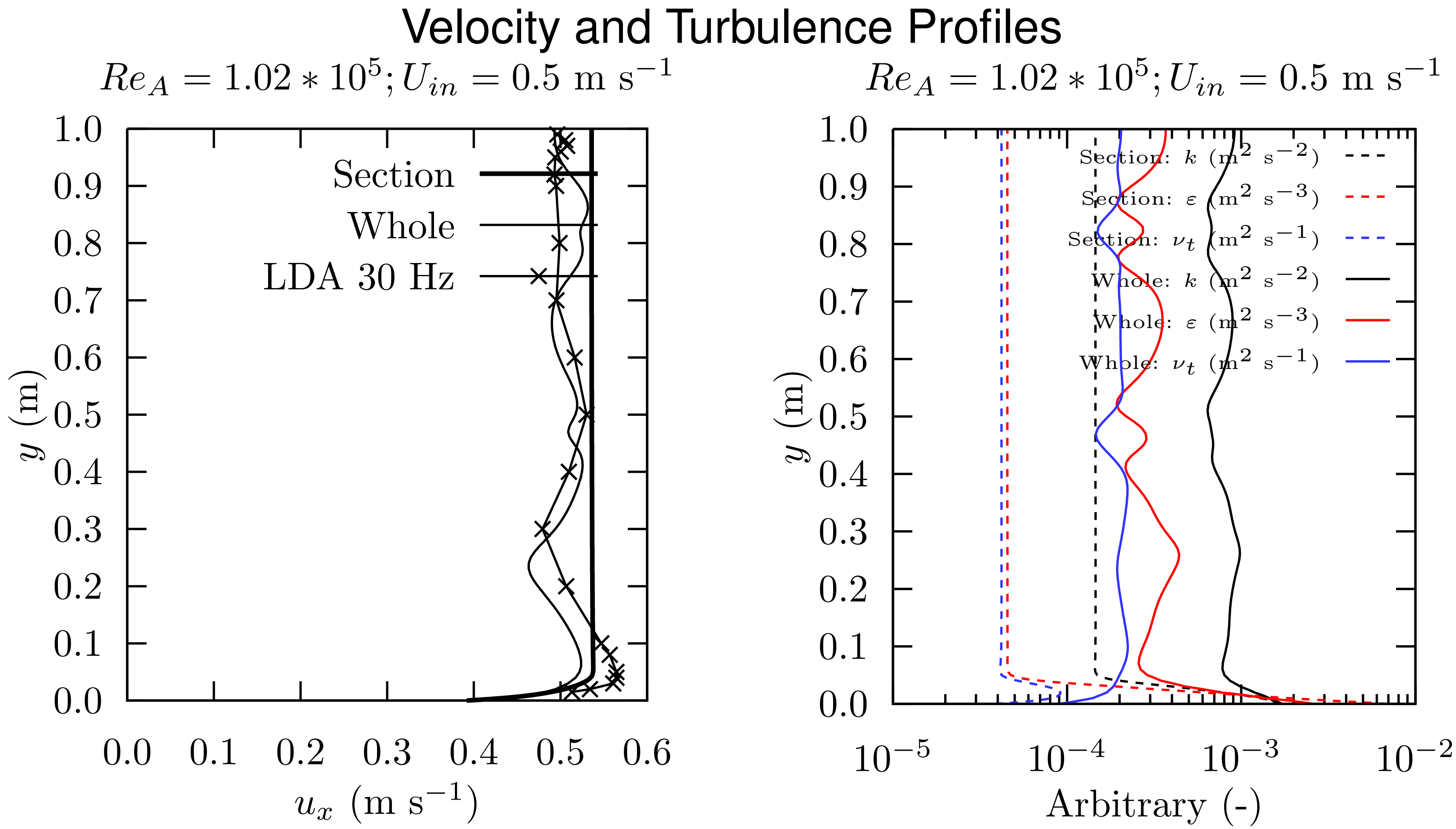
Experimental profiles

Profiles of Relative Turbidity (RT) measured in the channel



RT = Relative Turbidity; RT400 = Relative Turbidity at 0.4 m.

Experimental and numerical profiles

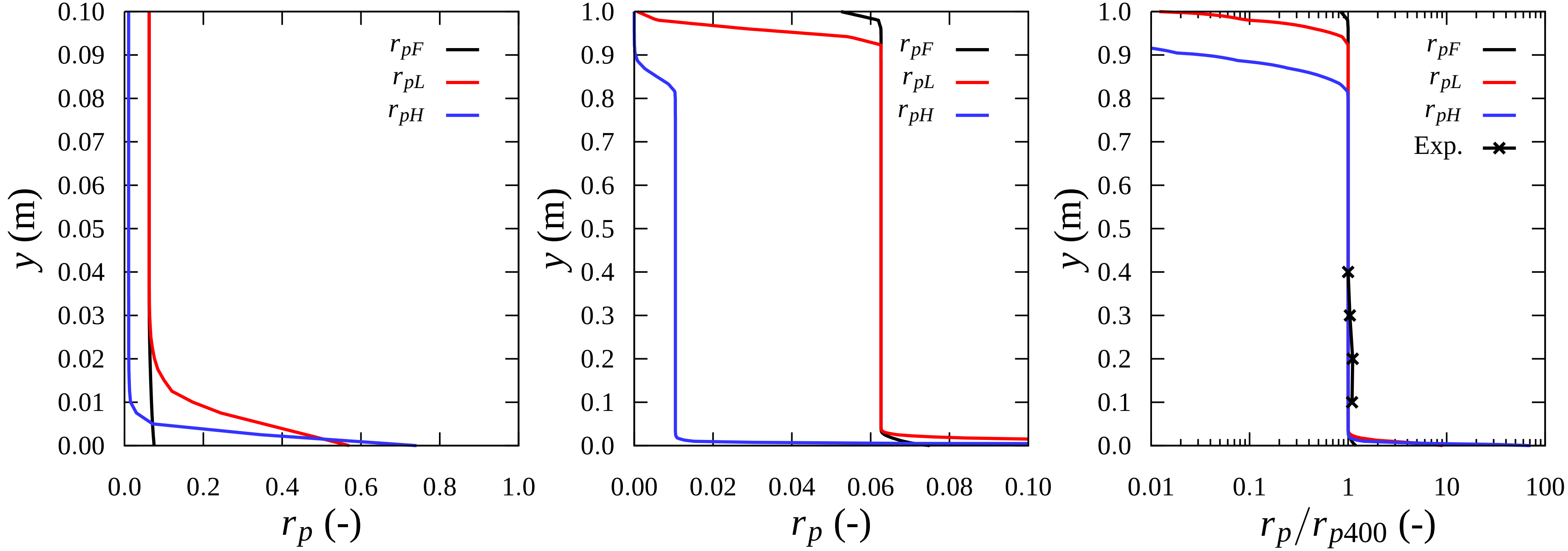


k = turbulent kinetic energy; u_x = horizontal velocity component; ε = turbulent eddy dissipation rate;

ν_t = turbulent viscosity;

Simulations with one dispersed phase

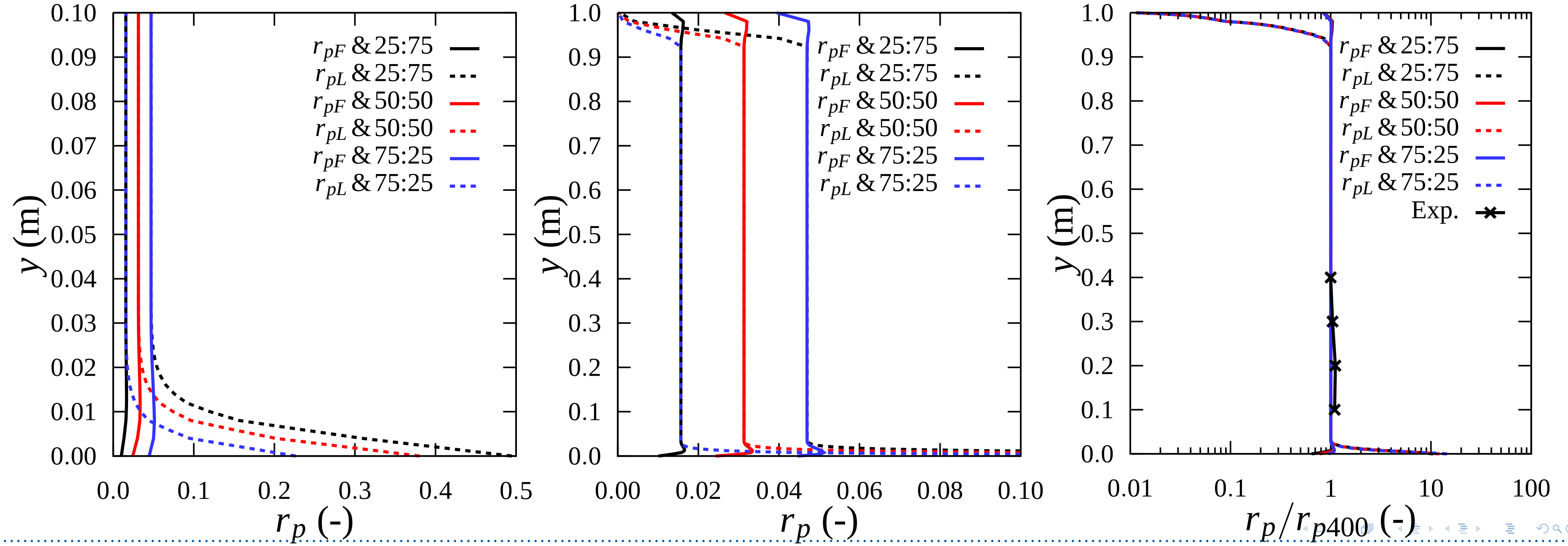
Parameter	pF	pL	pH
ρ_p (kg m^{-3})	1002	1002	1027
d_p (mm)	0.5	5	5
u_{tp} (m s^{-1})	$\sim$0.0005	$\sim$0.02	$\sim$0.05
r_p (-)	0.06263	0.06263	0.01044



r_{p400} = volume fraction at 0.4 m; $\rho_c = 997$ kg m^{-3} and $\mu_c = 8.899*10^{-4}$ kg m^{-1} s^{-1}

Simulations with two dispersed phases

Parameter	pF	pL
ρ_p (kg m^{-3})	1002	1002
d_p (mm)	0.5	5
u_{tp} (m s^{-1})	$\sim$0.0005	$\sim$0.02
$0.25r_{pF}$:$0.75r_{pL}$	0.01566	0.04698
$0.50r_{pF}$:$0.50r_{pL}$	0.03132	0.03132
$0.75r_{pF}$:$0.25r_{pL}$	0.04698	0.01566



Conclusions

- Uniform velocity profile has a significant effect on the volume fraction profiles
- Solids layer formed at the channel base for larger heavier phases, which is not observed in the experiments
- Varying the volume fraction of the lighter phases in simulations with two dispersed phases caused reductions in solids found near to the channel base
- Modifications to C_D and C_{TD} can also reduce the maximum volume fractions observed
- Further simulations modelling the whole channel are necessary
- Evaluation is also required for the closure of the mixture viscosity
- Improved experiments are also essential

Acknowledgments

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- This project is not part of the oversight process and does not intend to deliver safety guidelines