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
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
    \( (Re \sim 10.4 \times 10^4 \text{ or } 0.5 \text{ m s}^{-1}) \)
  + 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

1  2  3  4  5

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

\[ d_p = \text{particle diameter}; \quad N_p = \text{Number of agglomerates}; \quad u_{tp} = \text{terminal settling velocity} \]
Dispersed phase morphology

- Assumed spherical agglomerate of wetted fibers

- Knowing both $d_p$ and $u_{tp}$, $\rho_p$ 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

\[
\mu_r = 1 + 2.5r_p + 7.6r_p^2 \quad \text{(Batchelor, 1977)}
\]

$r$ = volume fraction; $\mu$ = dynamic viscosity; $\rho$ = density; $\zeta$ = fiber share; Subscripts: c = continuous; cp = mixture; f = individual fiber; r = relative; p = dispersed;
Interphase Forces

- Buoyancy force characterises the motion of the particles
  \[ \vec{S}^B_{cp} = \vec{g} r_p (\rho_p - \rho_c) \]

- Drag Force characterises the resistance of the particles to fluid flow
  \[ \vec{M}^D_{cp} = C^D_{cp} (\vec{u}_p - \vec{u}_c) \]

- 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
  \[ C^D_{cp} = \frac{3}{4} \frac{C_{D,SN}}{d_p} r_p \rho_c |\vec{u}_p - \vec{u}_c| \]

\[ C^D_{cp} = \text{momentum exchange coefficient}; \ C_{D,SN} = \text{Schiller-Naumann drag coefficient}; \ d_p = \text{particle diameter}; \]
\[ C_{TD} = \text{turbulence dispersion coefficient}; \ \vec{g} = \text{gravitational acceleration}; \ \vec{M} = \text{interfacial force}; \ r = \text{volume fraction}; \ \vec{S} = \text{body or external force}; \ \vec{u} = \text{mean velocity vector}; \ \nu_{tc} = \text{kinematic turbulent viscosity}; \ \rho = \text{density}; \ \sigma_{tc} = \text{turbulent Prandtl number}; \ \text{Superscripts: B = buoyancy; D = drag; TD = turbulence dispersion} \]
Experimental profiles

Profiles of Relative Turbidity (RT) measured in the channel

$RT = \text{Relative Turbidity; } RT400 = \text{Relative Turbidity at } 0.4 \text{ m.}$
Experimental and numerical profiles

Velocity and Turbulence Profiles

$Re_A = 1.02 \times 10^5; U_{in} = 0.5 \text{ m s}^{-1}$

$k = \text{turbulent kinetic energy}; u_x = \text{horizontal velocity component}; \varepsilon = \text{turbulent eddy dissipation rate}$;

$\nu_t = \text{turbulent viscosity}$;
Simulations with one dispersed phase

<table>
<thead>
<tr>
<th>Parameter</th>
<th>pF</th>
<th>pL</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_p$ (kg m$^{-3}$)</td>
<td>1002</td>
<td>1002</td>
<td>1027</td>
</tr>
<tr>
<td>$d_p$ (mm)</td>
<td>0.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$u_{lp}$ (m s$^{-1}$)</td>
<td>$\sim$0.0005</td>
<td>$\sim$0.02</td>
<td>$\sim$0.05</td>
</tr>
<tr>
<td>$r_p$ (-)</td>
<td>0.06263</td>
<td>0.06263</td>
<td>0.01044</td>
</tr>
</tbody>
</table>

$r_{p400}$ = volume fraction at 0.4 m; $\rho_c = 997$ kg m$^{-3}$ and $\mu_c = 8.899 \times 10^{-4}$ kg m$^{-1}$ s$^{-1}$
Simulations with two dispersed phases

<table>
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<td>$d_p$ (mm)</td>
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<td>5</td>
</tr>
<tr>
<td>$u_{tp}$ (m s$^{-1}$)</td>
<td>$\sim0.0005$</td>
<td>$\sim0.02$</td>
</tr>
</tbody>
</table>

0.25$r_{pF}$:0.75$r_{pL}$ 0.01566 0.04698
0.50$r_{pF}$:0.50$r_{pL}$ 0.03132 0.03132
0.75$r_{pF}$:0.25$r_{pL}$ 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
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- This project is not part of the oversight process and does not intend to
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