Numerical Analysis on the Particle Behaviour in a Fluid Phase Resonance Mixer

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Introduction and Motivation

Numerical calculations fluid and particles

Validation of fluid flow calculations based on LDA measurements

Influence of fluid forces on particle distribution

Influence of Stokes number on particle distribution

Conclusions/Outlook
Principle of Fluid-Phase-Resonance (FPR) Mixer

Drive
Central Pipe
Gas Cushion
Mixing Vessel

Martin-Luther-Universität Halle-Wittenberg
Development of research project on FPR mixing based on simulations with OpenFOAM

**Initial configuration of FPR**
- Simulations for axisymmetric geometry
- Grid independency study
- Validation of simulations with LDA measurements
- Conclusions for improvements

**New configuration for intense mixing**
- Simulations for half the vessel
- Validation of simulations with LDA measurements
- Comparison with initial model

Simulation of particle behaviour
- Using the last period as the flow field
- Simulation for different particle properties (Stokes number)
Summary of fluid flow simulations
- OpenFOAM (compressibleInterFoam)
- $k-\omega$-SST turbulence model
- Grid generation with snappyHexMesh (3 million)
- Vessel geometry: $d_{vessel} = 0.45 \text{ m}; h_{water} = 0.7 \text{ m} \quad d_{pipe} = 0.1 \text{ m} \quad f_{FPR} = 1.2 \text{ Hz}$

Boundary conditions at liquid surface:

$$U_z(t) = \sin \left( 2 \pi f_{FPR} t \right) \cdot \begin{pmatrix} 0 \\ 0 \\ U_{max} \end{pmatrix} \rightarrow \dot{V}_{max} = 0.0071 \text{ m}^3/\text{s}$$

Fluid properties:

- Density [kg/m³]: 998 (w) 1.292 (a)
- Kinematic viscosity [10⁻⁶ m²/s]: 1.004 (w) 13.3 (a)
- Compressibility [10⁻⁹ s²/m²]: 0.47 (w) 9901 (a)

Simulation of 10 s (12 periods); the last periods (~ 0.83 s) was used
Lagrangian tracking of particles, neglecting two-way coupling

- Tacking repeatedly for the last period; about 24.9 s (30 periods); Lagrangian time step 0.0001 s
- For forces: drag, pressure force, gravity/buoyency, slip-shear lift, slip-rotation lift (Crowe et al. 2012):
  \[
  m_p \frac{d u_{p,i}}{dt} = \frac{3}{4} \frac{\rho}{\rho_p D_p} m_p C_D (u_i - u_{p,i}) |\vec{u} - \vec{u}_p| + \frac{\rho_f \pi}{2} D_p^2 C_{LS} D_p \left( (\vec{u}_F - \vec{u}_p) \times \vec{\omega}_F \right) \\
  + \frac{\rho_f \pi}{2} D_p^2 C_{LR} |\vec{u}_F - \vec{u}_p| \frac{\vec{\Omega} \times (\vec{u}_F - \vec{u}_p)}{|\vec{\Omega}|} + m_p g_i \left( 1 - \frac{\rho}{\rho_p} \right) + m_p \frac{\rho_f}{\rho_p} \frac{D \vec{u}_F}{D t} 
  \]
- Gradient dispersion model
- Inelastic wall collision model: \( e = 0.96; \mu = 0.1 \)
- 1000 particles were initially homogeneously distributed at the end of the central pipe
- Particle sizes: 0.04, 0.5, 2.0, 2.5, 3.5 mm (\( \rho_p = 2500 \) kg/m\(^3\))
- Particle Stokes numbers: 3.2E-4, 0.05, 0.8, 1.25 and 2.45

\[
St_p = \tau_p f_{FPR} \quad \tau_p = \frac{(\rho_p + 0.5 \rho_1) d_p^2}{18 \mu_1}
\]
Fluid Flow Results

➤ Comparison of simulations (top) with LDA measurements (bottom)

\[ U_{i,max,min} = \frac{1}{N_{\Delta t}} \sum_{n=1}^{N_{\Delta t}} \min, \max \left( u_{i,n} \mp 3/2\sqrt{k} \right) \]

\[ U_{Ave} = \frac{1}{T} \sum_{t=0}^{T} u(t) \]
Particle-Phase Results 1

- Instantaneous particle distribution projected in one plane at the end of the simulation, influence of different particle forces ($St = 0.025$).

a) all forces  
b) no gravity/buoyancy  
c) no pressure force  
d) No slip-rotation  
e) No slip-shear  
f) No lift forces
Vertical profiles of particle concentration at the end of the simulation

\[ c_n = \frac{n_{p,s}}{V_s} \frac{1}{n_p/V_l} \]

\[ \text{St} = 0.025 \]

\[ h_{\text{slice}} = 0.07 \text{ m} \]
Particle-Phase Results 3

- Instantaneous particle distribution projected in one plane at the end of the simulation, influence of particle Stokes number.

a) $St = 3.2 \times 10^{-4}$
b) $St = 0.05$
c) $St = 0.8$
d) $St = 1.25$
e) $St = 2.45$
Vertical profiles of particle concentration at the end of the simulation with the Stokes number as a parameter.