Aggregation and breakage of solid particles in a turbulent flow through a 90◦ pipe bend using CFD-PBE

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Keywords: *Multiphase flow; Aggregation; Breakage; Population balance equation; MultiphaseEulerFoam*

The aggregation and breakage of particles in turbulent flows are of interest for many industries and applications. Several modelling procedures have been applied to dilute particle-laden flow to predict the aggregation and breakage of adhesive particles. The multiphase Euler-Euler method, where both the particle and fluid phases are modelled as continuous fields has proven beneficial for industrial-scale applications with micron-sized particles, as the number of particles otherwise becomes too large for typical Lagrangian methods. The population balance equation (PBE) is applied to account for the number density function of the particles in the computational domain. Several methods have been proposed to solve the PBE, where several are based on the method of moments (MOM). Some of the most common types of MOM are Quadrature MOM (QMOM), Direct QMOM (DQMOM) and Extended QMOM (EQMOM). An alternative approach to solve the PBE is the class method, which is implemented in the OpenFOAM multiphase Eulerian framework in the solver `multiphaseEulerFoam` [1]. The polydisperse number density function is discretised into several size classes, thereby making the method straightforward and intuitive at the expense of a higher computational cost compared to the MOM methods.

The aggregation and breakage models for solid particles are described and implemented into the `multiphaseEulerFoam` framework in this study. Furthermore, interfacial momentum transfer is taken into account and the Saffman-Mei lift force is implemented into the `multiphaseEulerFoam` framework. The models are developed for OpenFOAM v9 and are accessible at the HZDR OpenFOAM Addon [2]. The modelling framework is then used to study the particle size distribution of micron-sized particles downstream of a 90° pipe bend for a turbulent fluid flow with a Reynolds number of $Re_{\mathrm{f}} = 20,000$.

Numerical framework: The continuity- and momentum equations for the multiphase Eulerian framework is seen in (1) and (2).

$$\frac{\partial}{\partial t}\left(\alpha_\varphi \rho_\varphi\right) + \nabla \cdot \left(\alpha_\varphi \rho_\varphi \vec{u}_\varphi\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\alpha_\varphi \rho_\varphi \vec{u}_\varphi\right) + \nabla \cdot \left(\alpha_\varphi \rho_\varphi \vec{u}_\varphi \vec{u}_\varphi\right) - \nabla \cdot \tau_\varphi = -\alpha_\varphi \nabla p + \alpha_\varphi \rho_\varphi \vec{g} + \vec{M}_\varphi + \vec{S}_\varphi \tag{2}$$

where φ denotes each phase, α is the void fraction, ρ is the density, $\vec{u}$ is the velocity, τ is the stress tensor, p is the pressure, $\vec{g}$ is the gravitational acceleration, M is the rate of interfacial momentum transfer and S is the momentum source term. Since the flow is turbulent and the geometrical setup introduces swirling in the flow, the RNG k-ε is applied to account for the Reynolds stresses. The class method for the PBE implemented in the `multiphaseEulerFoam` framework is seen in (3). The PBE is solved for each discretised size class.

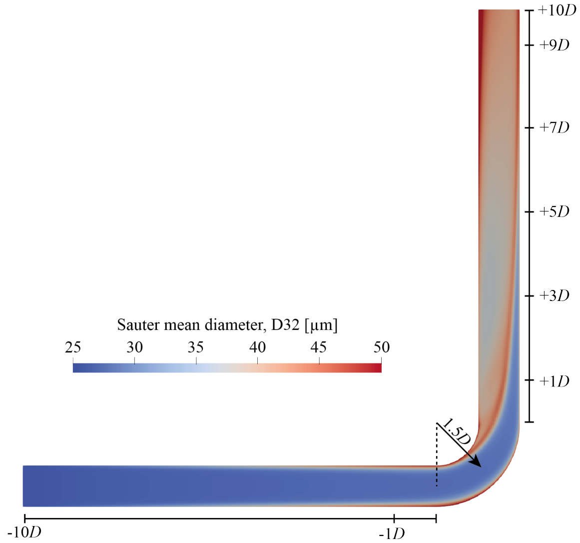
$$\frac{\partial N_i}{\partial t} + \nabla \cdot \left(\vec{u} N_i\right) = S_i \tag{3}$$

where subscript i denotes each size group, N is the number of particles and S is the source term account for discontinuous changes in the number density function such as aggregation and breakage.

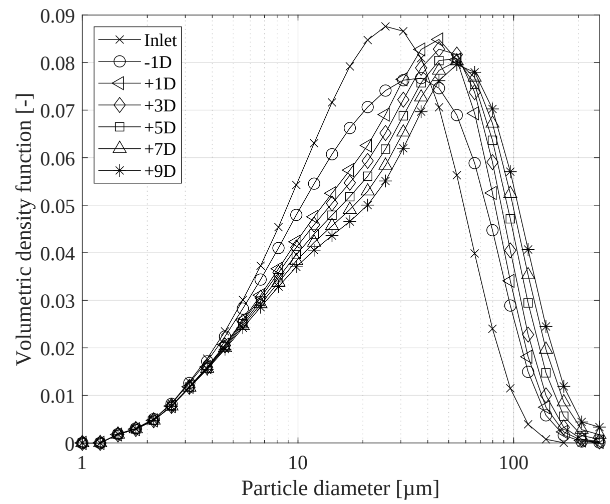
In this study, the drag-, lift-, virtual mass and turbulent dispersion force are implemented as interfacial momentum transfers. The drag coefficient is based on [3] where the drag coefficient is a function of the particle Reynolds number, Re_{p} and the particle volume fraction, α_{p}. The Saffman-Mei lift force model for finite Reynolds number is implemented in the multiphase Eulerian framework [4]. A constant virtual mass coefficient of $C_{\mathrm{VM}} = 0.5$ is applied and a Favre averaged turbulent dispersion force model is applied [5].

The turbulent aggregation kernel, β, by [6] can be seen in (4) and the breakage kernel, ζ, by [7] can be seen in (5). The breakage kernel requires a daughter distribution function and a discretised beta distribution function is applied. The aggregation and breakage kernels for solid particles and the Saffman-Mei lift model are implemented in the multiphase Eulerian framework and are freely available at the HZDR Multiphase Addon for OpenFOAM [2].

$$\beta = \frac{4}{3}\left(\frac{3\pi}{10}\right)^{0.5}\left(\frac{\varepsilon}{\nu}\right)\left(v_i + v_j\right)^3 \tag{4}$$



(a) Sauter mean diameter for the computational domain



(b) Initial- and downstream particle size distributions.

$$\zeta = \left(\frac{4}{15\pi}\right)^{0.5} \left(\frac{\varepsilon}{\nu}\right)^{0.5} \exp\left(-\frac{\varepsilon_{\rm cr}}{\varepsilon}\right) \tag{5}$$

where ε is the turbulent dissipation rate of the fluid, ν is the kinematic viscosity of the fluid, $v_{i,j}$ is the volume of particle i and j and $\varepsilon_{\rm cr}$ is the critical turbulent energy dissipation rate at which the agglomerates break.

Results: The particle size distribution is analysed for a $90°$ pipe bend with a bending radius of $r_{\rm b} = 1.5D$ with a dilute particle volume fraction of $\alpha_{\rm p} = 10^{-3}$. A length of $10D$ before and after the pipe bend is introduced, as seen in Fig. 1a. The initial particle size distribution is seen in Fig. 1b and a density ratio of $\rho_{\rm p}/\rho_{\rm f} = 1.4$ between the continuous and discrete phase. The Sauter mean diameter, $D_{3,2}$ is seen in Fig. 1a and the particle size distribution for the inlet and at different positions downstream of the pipe bend is seen in Fig. 1b. From Fig. 1a it is seen that the particle size increases over the length of the geometry, but that the mean particle diameter increases significantly downstream of the pipe bend. As the particles move further downstream, the Sauter mean diameter increases further, which is both seen in Fig. 1a and 1b.

Conclusions: In this study, the population balance equation was successfully used in the multiphase Eulerian framework to describe the aggregation and breakage of micron-sized particles. The breakage and aggregation kernels were successfully implemented into the `multiphaseEulerFoam` framework as well as the interfacial lift force model.

The study shows how to model agglomeration and breakage of dilute particles in turbulent flows through a 90° pipe bend and how the particle size distribution increases downstream of the 90° pipe bend for the given particle properties.

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