EPJ Web of Conferences **340**, 08007 (2025)
Powders & Grains 2025
https://doi.org/10.1051/epjconf/202534008007

Fully-resolved modelling of suspension flows: an overview

Mohammad Fazli[1,2,*], *Murray* Rudman[1], *Shibo* Kuang[2], and *Aibing* Yu[2]

[1]Department of Mechanical & Aerospace Engineering, Monash University, Clayton, 3800, Victoria, Australia
[2]ARC Research Hub for Smart Process Design and Control, Monash University, Clayton, 3800, Victoria, Australia

Abstract. Suspension flows in industrial processes, such as transportation and sedimentation, are strongly influenced by fluid-particle interactions. The presence of different-sized particles in mineral slurry flows alters suspension rheology and shear response, leading to complex flow behaviour, including size-induced segregation. This study employs a fully-resolved CFD-DEM framework, integrating the Immersed Boundary Method (IBM) with the Discrete Element Method (DEM), to investigate suspension flows with varying particle sizes and non-Newtonian rheology. The developed model captures intricate particle-fluid interactions, sedimentation dynamics, and shear-induced segregation, which are critical for applications such as tailings transport and thickener performance optimization. The results provide insights into the influence of rheology on settling behaviour and highlight the significance of particle size segregation in determining flow characteristics during sedimentation/transportation. These findings contribute to the development of improved drag correlations and transport models for high-concentration suspensions in industrial applications.

1 Introduction

Particulate flows play a vital role in industries such as mining, water treatment, and food processing. In mining, managing tailings—the waste from mineral extraction—is a significant challenge, with global production reaching approximately 14 billion tons in 2010 [1]. Tailings are typically transported as slurries to large storage facilities known as tailings dams. Conventional transport methods rely on slurries with low solid concentrations (<30% w/w), resulting in excessive water consumption, rapid dam filling, and heightened environmental risks. In arid regions such as Australia and Chile, reducing water consumption in mineral processing is essential to addressing ecological and economic challenges, including dam stability concerns and landscape contamination.

Advancements in thickener technology have enabled the use of higher-concentration tailings suspensions, significantly reducing environmental impact. Thickeners function by removing excess water through sedimentation, yielding a denser underflow with enhanced stability. Increasing tailings concentration from 30% to 50% w/w can reduce water discharge in dams by 60%, minimizing land use and improving dam stability [2]. However, slurries contain particles of varying sizes, from fine to coarse. As water is removed, fine particles mix with the remaining fluid, causing thickened slurries to exhibit non-Newtonian behaviour—specifically yield-pseudoplastic characteristics—that alter their interaction with particles [3]. Understanding these complex fluid-particle interactions is crucial for optimizing pipeline transport and sedimentation processes.

To investigate these interactions, we developed and implemented a fully-resolved CFD-DEM approach that couples the Immersed Boundary Method (IBM) with the Discrete Element Method (DEM) for particle flow modelling. The presence of a wide particle size distribution affects settling dynamics and fluid-particle interactions, which are critical for optimizing thickener performance and pipeline transport. This paper provides an overview of our investigations into how rheology and polydispersity in suspensions influence sedimentation and shear-induced segregation, including results published in [4–6].

2 Methodology

CFD-DEM is a method based on the Eulerian-Lagrangian approach, which gives detailed information on individual particles trajectories. The *CFDEMcoupling* package [7] contains some solvers based on this approach. In this package, the CFD calculation is conducted using OpenFOAM-based solvers while the particle/particle interaction is simulated by a DEM code, LIGGGHTS. For the CFD part, the incompressible Navier-Stokes equations are solved:

$$\nabla . u = 0 \quad \text{in} \ \Omega \tag{1}$$

$$\frac{\partial\left(\rho_f u\right)}{\partial t} + \nabla . \left(\rho_f u u\right) = -\nabla p + \nabla . \tau \quad \text{in} \ \Omega \tag{2}$$

The current study aims to resolve the interactions; therefore, the IB solver, *cfdemSolverIB*, from the *CFDEMcoupling* package is utilized. This solver employs a version of the IBM, in which the presence of the particles is detected by calculating the fluid void fraction (ε_f) over the Cartesian grid, as shown in Figure 1. The cells that are entirely covered by the particles get the value of void fraction

---

[*] e-mail: mohammad.fazli1@monash.edu

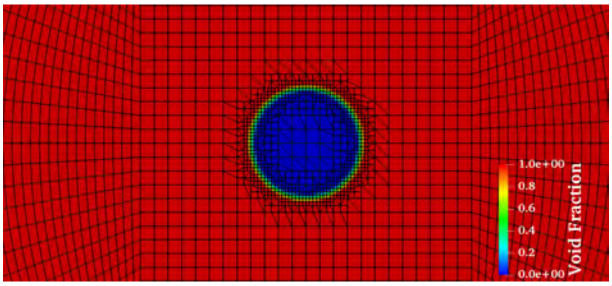


Figure 1. Dynamic mesh refinement near the particle interface

equal to zero ($\varepsilon_f = 0$), while those containing just the fluid are assigned a value of one ($\varepsilon_f = 1$). There are some cells at the interface that are partially covered by the fluid and by the particle. For these cells, the void fraction is calculated based on the fractional volume covered by the particle. Therefore, to accurately detect the particle interface, a dynamic grid refinement approach is used as shown in the figure. For the solid phase in DEM, Newton's second law is employed:

$$\begin{aligned} m_i \frac{\mathrm{d}U_i^p}{\mathrm{d}t} &= \sum_{j=1}^{n_i^c} F_{ij}^c + F_i^f + F_i^g + m_i g, \\ I_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} &= \sum_{j=1}^{n_i^c} M_{ij}^c + M_i^f \end{aligned} \tag{3}$$

in which m_i and I_i denote mass and moment of inertia for particle i, U_i^p and ω_i are the translational and angular velocity of the particle, F_{ij}^c and M_{ij}^c represent the contact force and torque, F_i^f and M_i^f are the interaction force and torque acting from fluid on the particle, and F_i^g is the buoyancy force.

The boundary conditions at the interface of fluid and particles are:

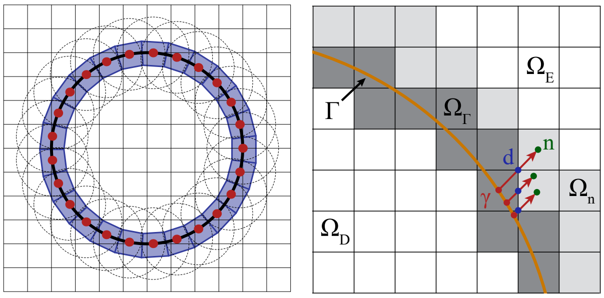
$$u = u_i \quad \text{and} \quad (-p\mathrm{I} + \tau)\,.\hat{n} = t_{\Gamma_s} \quad \text{on } \Gamma_s \tag{4}$$

where u_i denotes the particle interface velocity and t_{Γ_s} represents the traction vector of the fluid on the particle surface. In the Immersed Boundary Method, these rigidity constraints are imposed through different approaches in the interface region, either by Lagrangian points (Figure 2(a)) or ghost-cell interpolation (Figure 2(b)). By integrating the stress condition over the particle interface and using Gauss theorem, the following relation for interaction force is obtained:

$$\begin{aligned} F_i^f &= \int_{\Gamma_s} (-p\mathrm{I} + \tau)\,.\hat{n} d\Gamma_s = \int_{\Omega} \left[-\nabla p + \nabla.\tau\right] \delta_x d\Omega \\ &= \sum_{c \in T_h} (-\nabla p + \nabla.\tau)(c) V(c) \end{aligned} \tag{5}$$

Similar to the procedure presented above, the torque acting on particle, M_i^f, is calculated by:

$$M_i^f = \sum_{c \in T_h} \left[r(c) \times (-\nabla p + \nabla.\tau)(c)\right] V(c) \tag{6}$$



(a) Lagrangian points (b) Ghost-Cell Interpolation

Figure 2. Imposing particle rigidity constraints by different IBM approaches [4]

The buoyancy (F_i^g) is the upward force exerted on the immersed object because of the displaced fluid. It can be obtained from the following equation:

$$F_i^g = \sum_{c \in T_h} \left(\rho_f g\right)(c) V(c) \tag{7}$$

In Eq. (3), F_{ij}^c and M_{ij}^c are calculated by the non-linear elastic Hertz-Mindlin model [8]. In this model, the total contact force (F^c) is modelled by the summation of a normal contact ($F^{c,n}$) and tangential contact ($F^{c,t}$) force components. Each of these forces comprises a damping (damper) and an elastic (spring) part, which are defined as:

$$\begin{aligned} F^c &= F^{c,n} + F^{c,t} \\ F^{c,n} &= -k_n \delta_n + c_n \Delta u_n \\ F^{c,t} &= min \left\{ \left| k_t \int_{t_{c,0}}^{t} \Delta u_t dt + c_t \Delta u_t \right|, \eta F^{c,n} \right\} \end{aligned} \tag{8}$$

in which k_n, k_t, and c_n, c_t are the normal and tangential elastic and damping constants, respectively, δ_n is the normal overlap between two contacting surfaces, Δu_n, Δu_t are the normal and tangential components of relative velocities between these surfaces, and finally, η is the Coulomb friction coefficient.

3 Results and Discussions

The presence of carrier water in slurries, combined with very fine tailings materials, results in a distinct fluid exhibiting non-Newtonian rheology characterized by a yield-pseudoplastic model, i.e., the Herschel–Bulkley model [9]. This non-Newtonian fluid begins to flow only after exceeding a specific external stress threshold (yield stress); before this point, it behaves as a rigid body without deformation. The fluid exhibits a wide range of viscosity values depending on shear rate. After yielding, its shear stress-shear rate relationship becomes non-linear. In this case, the IBM used for simulating particle flow in non-Newtonian fluids must account for the wide viscosity variations and accurately enforce rigidity constraints to capture fluid-particle interactions.

https://doi.org/10.1051/epjconf/202534008007

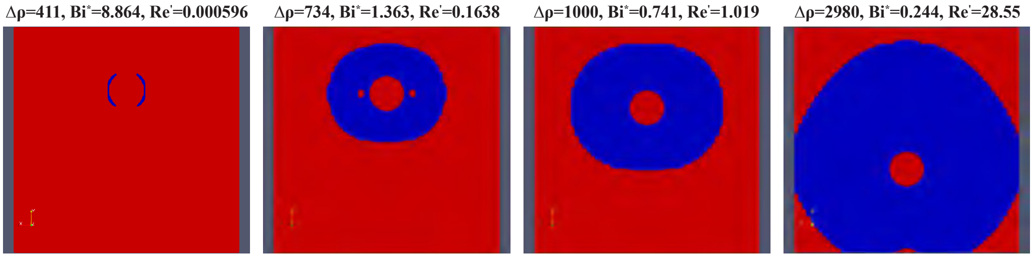


Figure 3. The predicted yielded region by IBM-DEM around a single particle settling in a yield-pseudoplastic fluid [4]

To investigate the sedimentation process in a non-Newtonian flow, the developed solver is applied to the settling of a single particle. A resolution criterion of 8 grid cells per particle diameter is used for the simulation, along with a level-2 refinement at the particle–fluid interface, as depicted in Figure 1. This grid arrangement provides local refinement at the interface, offering a reasonable balance between computational time and accuracy [5].

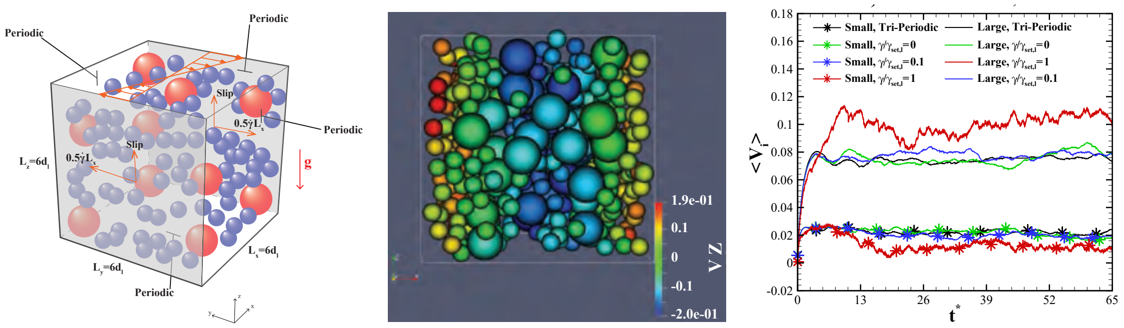
Figure 3 illustrates the yielded region around the settling particle in fluids with different rheological properties. These properties vary depending on the tailings material, as different materials exhibit distinct yield stresses and non-linear shear stress-shear rate behaviour. As shown in Figure 3, the size of the yielded region around the settling particle enlarges depending on the characteristics of the tailings material. The results demonstrate the precise imposition of boundary conditions by the Immersed Boundary Method, enabling accurate calculation of fluid–particle interactions in a non-Newtonian yield-pseudoplastic fluid.

The outcome of this investigation can be applied to developing a drag correlation for particle-fluid interactions in thickened slurries, which must be transported to storage sites. Using the proposed IBM, comprehensive data can be generated under various rheological conditions in multi-particle suspension flows. The predictions from these simulations contribute to a robust drag correlation for this non-Newtonian fluid, which is essential for designing pipeline systems for slurry transport.

The thickened slurry from the thickener can still be treated as a mixture of fine and coarse particles suspended in a Newtonian carrier fluid [5, 6]. The second part of this study examines the distribution and settling behaviour of different-sized particles in thickened slurries under shear, mimicking the effect of the pipeline wall during transport. A bidisperse system of small and large particles was chosen as the simplest representation of a system with varying particle sizes, capturing essential features without unnecessary complexity. As shown in Figure 4(a), shear generated by two moving sidewalls can induce size segregation in a suspension with a diameter ratio of $l = 2$, affecting particle-fluid interactions and, consequently, sedimentation in the pipe. Figure 4(b) illustrates shear-induced segregation, where large particles accumulate in the center, while smaller particles concentrate near the walls. This size-dependent accumulation significantly influences particle-fluid interactions during sedimentation.

Figure 4(c) shows that smaller particles exhibit a reduced sedimentation rate as shear increases. This reduction in settling velocity correlates with their displacement toward the near-wall region, as illustrated in Figure 4(b). In contrast, larger particles, concentrated in the center, are less influenced by shear and exhibit a significant increase in settling velocity. These findings suggest that size segregation plays a crucial role in particle-fluid interactions in sheared systems.

Building on the size-induced segregation, the transport of bidisperse slurries is simulated in pipe flow using the IBM approach. Figure 5 illustrates three pipes transporting particles in fluid flow, with a focus on how the transport of large particles is affected when a specific volume of large particles is replaced by smaller ones. The investigation reveals that introducing smaller particles into a monodis-



(a) Sheared domain

(b) Particles distribution

(c) Particles settling velocity

Figure 4. Effect of shear rate generated by moving walls on a bidisperse system with $l = 2$ [6]

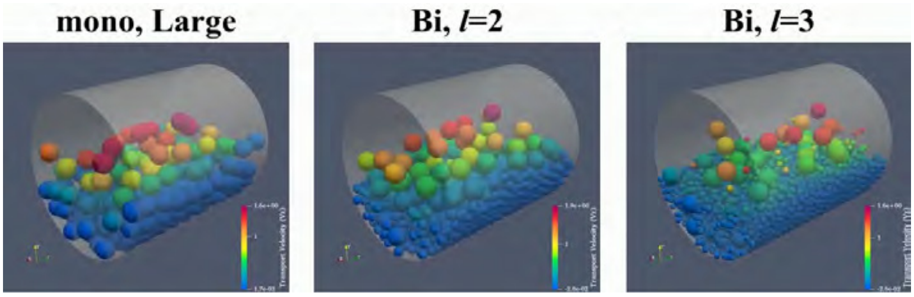


Figure 5. Pipe flows transporting monodisperse and bidisperse particle systems

perse suspension of large particles leads to the formation of a particle bed at the bottom of the pipe, over which the larger particles slide. Consequently, bidisperse systems exhibit different interactions between large particles and the freestream flow, as shown in Figure 5, ultimately resulting in a different transport rate when smaller particles are present.

Figure 6 further illustrates how the position and velocity of large particles change when bidisperse slurries are transported through a pipe. The results clearly demonstrate size segregation, with large particles shifting to higher vertical positions, which in turn leads to increased transport velocity. These findings provide important insights into the behaviour of slurries containing different-sized particles—knowledge that is essential for optimizing pumping systems and ensuring the efficient, cost-effective transport of industrial slurries.

References

[1] Jones, H. & Boger, D., Sustainability and waste management in the resource industries. Industrial & Engineering Chemistry Research **51**, 10057-10065 (2012).

[2] Treinen, J., *Modelling transport and deposition of coarse particles in viscoplastic tailings beach flows* (University of Colorado at Boulder,2017)

[3] Slatter, P., The rheological characterisation of sludges. Water Science And Technology **36**, 9-18 (1997).

[4] Fazli, M., Rudman, M., Kuang, S. and Chryss, A., Application of immersed boundary methods to non-Newtonian yield-pseudoplastic flows. Applied Mathematical Modelling **124**, 532-552 (2023).

[5] Fazli, M., Rudman, M., Kuang, S. & Chryss, A., Predicting bidisperse particle settling from mono-sized settling systems. Powder Technology **437**, 119545 (2024).

[6] Fazli, M., Rudman, M., Kuang, S. and Chryss, A., The effect of shear-induced segregation on bidisperse suspension settling. Powder Technology **442**, 119881 (2024).

[7] Goniva, C., Kloss, C., Deen, N.G., Kuipers, J.A. and Pirker, S., Influence of rolling friction on single spout fluidized bed simulation. Particuology **10**, 582–591 (2012).

[8] Kloss, C., Goniva, C., Hager, A., Amberger, S. and Pirker, S., Models, algorithms and validation for open-source DEM and CFD–DEM. Progress in Computational Fluid Dynamics **12**, 140–152 (2012).

[9] Herschel, W., & Bulkley, R., Konsistenzmessungen von gummi-benzollösungen. Kolloid-Zeitschrift **39**, 291-300 (1926).

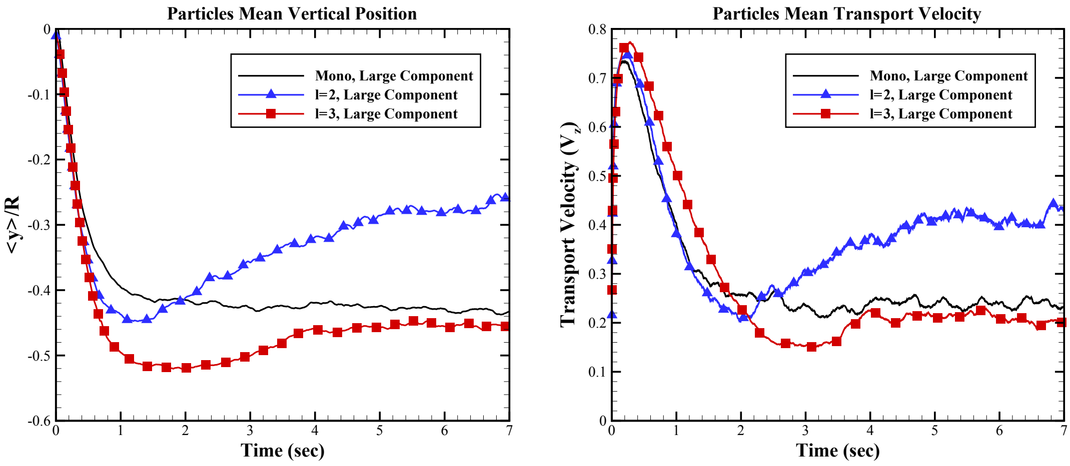


Figure 6. Mean vertical position and mean transport velocity of particles in pipe flow