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A Continuum-Based Mesh-Free Model for Simulating Floating Granular Materials

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ABSTRACT

Granular materials flowing in water bodies are common in many hydro-environmental processes. Examples include river ice transport during freeze-up and breakup, the spread of buoyant microplastics in aquatic environments, and the containment of floating debris after industrial spills, all of which can have significant environmental and socio-economic consequences. Developing predictive tools to model these complex phenomena is crucial for mitigating related hazards. Simulating floating granular materials poses challenges for Computational Fluid Dynamics (CFD) methods due to their highly nonlinear, multiphase interactions. Simulating the complex mechanical behavior of fluid-granular systems requires advanced numerical techniques and the adoption of appropriate governing equations.

Numerical modeling studies on the development of accurate and reliable CFD methods for granular dynamics are an ongoing investigation. Most existing works focus on fully immersed granular materials with high density values. CFD models with oversimplified assumptions in their governing equations often struggle to accurately capture the discrete and interfacial characteristics of floating granular materials. Discrete-based models, such as the Discrete Element Method (DEM), widely used for particle-level simulations, offer detailed insights into the behavior of individual particles. However, these models can be computationally intensive and may not be suitable for large-scale or time-dependent simulations, where numerous pairwise interactions must be calculated. Modeling granular materials as a continuous mass and using mesh-free Lagrangian techniques allows for accurate results and improved computational performance, providing a scalable approach for simulating floating granular systems. In continuum-based multiphase CFD models, granular dynamics are characterized by rheological formulations, and the fluid phase interacts with the granular phase through interphase forces.

This study aims to develop and validate a continuum-based, multiphase, mesh-free numerical model using the Moving Particle Semi-implicit (MPS) formulation to simulate floating granular materials. The model solves the full Navier-Stokes equations ensuring a robust representation of the dynamic interactions between the granular phase and the ambient fluid. To predict the non-Newtonian behavior of the submerged granular materials, the simulations incorporate two rheological models: the Herschel-Bulkley model and the standard visco-plastic model. The MPS model is enhanced with techniques that ensure both numerical stability and accuracy. To validate the numerical model, we simulate a benchmark case involving the lock-release of buoyant particles over a denser liquid surface. Comparison with experimental data demonstrates the accuracy and reliability of the developed model, as it could predict flow patterns and runout distance, establishing it as a robust tool for simulating a wide range of floating granular systems.