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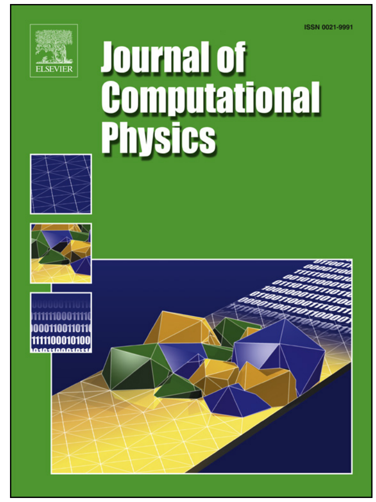

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A Solution Algorithm for Fluid–Particle Flows Across All Flow Regimes

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Abstract

Many fluid–particle flows occurring in nature and in technological applications exhibit large variations in the local particle volume fraction. For example, in circulating fluidized beds there are regions where the particles are close-packed as well as very dilute regions where particle–particle collisions are rare. Thus, in order to simulate such fluid–particle systems, it is necessary to design a flow solver that can accurately treat all flow regimes occurring simultaneously in the same flow domain. In this work, a solution algorithm is proposed for this purpose. The algorithm is based on splitting the free-transport flux solver dynamically and locally in the flow. In close-packed to moderately dense regions, a hydrodynamic solver is employed, while in dilute to very dilute regions a kinetic-based finite-volume solver is used in conjunction with quadrature-based moment methods. To illustrate the accuracy and robustness of the proposed solution algorithm, it is implemented in OpenFOAM for particle velocity moments up to second order, and applied to simulate gravity-driven, gas–particle flows exhibiting cluster-induced turbulence. By varying the average particle volume fraction in the flow domain, it is demonstrated that the flow solver can handle seamlessly all flow regimes present in fluid–particle flows.

Keywords: fluid–particle flow, kinetic theory of granular flow, quadrature-based moment methods, kinetic-based finite-volume methods, OpenFOAM

1. Introduction

Numerical simulations of fluid–particle flows are used in a wide range of fields, including energy applications such as fluidized beds [2, 17, 29, 30, 37, 51, 54, 55, 60, 65, 66] and risers [1, 9, 10, 15, 21, 22, 31, 40, 49, 57], and geophysical applications such as pyroclastic flows [18, 20], gravity currents [5] and sedimentation [3]. In this work, we are particularly interested in the numerical simulation of fluid–particle flows involving heavy (inertial) particles in a Newtonian fluid where the momentum exchange between the phases is dominated by drag. Furthermore, we consider flows wherein the disperse-phase volume fraction ranges from very dilute to dense (close-packed) conditions. In the absence of the fluid, the particle phase is modeled as a (rapid) granular flow based on a kinetic theory description [23, 32, 41]. The presence of the fluid phase modifies the particle momentum through a drag term in the kinetic equation for the one-particle velocity distribution function [24, 28, 39]. Due to hydrodynamic coupling through the drag term, even relatively dilute, gravity-driven, fluid–particle flows will exhibit particle clustering [1] and cluster-induced turbulence [9, 35]. Thus, within the same flow domain, a turbulent fluid–particle flow has time-dependent regions wherein the particle phase is nearly close-packed (i.e., clusters) separated by very dilute regions wherein particle–particle collisions are completely absent.

The range of applicability of computational approaches for the different fluid–particle flow regimes can be roughly characterized by two parameters: particle volume fraction, α_p, which reflects the relative frequency of particle–particle collisions, and particle Stokes number, $St_p = \tau_p/\tau_f$, where τ_p is the drag time and τ_f is the fluid time scale, which indicates how quickly the particle velocity reacts to variations in the fluid velocity. For sufficiently small St_p, particle velocity fluctuations are rapidly damped out, resulting in a very small granular temperature. With these

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