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Particle Collisions in a Lumped Particle Model

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Abstract. This paper presents an extension of the lumped particle model in [1] to include the effects of particle collisions. The lumped particle model is a flexible framework for the modeling of particle laden flows, that takes into account fundamental features, including advection, diffusion and dispersion of the particles. In this paper, we transform a binary collision model and concepts from kinetic theory into a collision procedure for the lumped particle framework. We apply this new collision procedure to investigate numerically the role of particle collisions in the hindered settling effect. The hindered settling effect is characterized by an increase in the effective drag coefficient C_D that influences each particle in the flow. This coefficient is given by $C_D=(1-\phi)^{-n}C_D^*$, where ϕ is the volume fraction of particles, C_D^* is the drag coefficient for a single particle, and $n\simeq 4.67$ for creeping flow. We obtain an approximation for C_D/C_D^* by calculating the effective work done by collisions, and comparing that to the work done by the drag force. In our numerical experiments, we observe a minimal value of $n=3.0$. Moreover, by allowing high energy dissipation, an approximation for the classical value for creeping flow, $n=4.7$, is reproduced. We also obtain high values for n, up to $n=6.5$, which is consistent with recent physical experiments on the sedimentation of sand grains.

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1 Introduction

Particle collisions are of paramount importance in dense particle laden flows. Such fluid flow appears in many processes in Nature, as well as in many industrial applications. Examples range from chemical synthesis engines to highly turbulent sand-laden subaquatic flow [27]. The complete understanding of the physics in these systems is of great scientific and economical value, and a large body of literature has been dedicated to studying these effects. In many of these physical phenomena, however, the exact effect of particle collisions is still under debate. This is especially the case for highly turbulent sand-laden flows. In a recent comprehensive review, Maiburg and Kneller [19] wrote: "Researchers will have to undertake high-resolution numerical simulations that track large numbers of individual particles to gain insight into the influence of particle-particle interactions". As stated in [19], there is still a need to develop new numerical models for particle collisions in these fluid flows, and the present paper describes the development of such a model.

There are numerous ways of modeling the effects of particle collisions. The most commonly used approach is the discrete particle methods. Here, each particle's position and velocity are obtained by the application of Newton's second law of motion [24]. This equation is coupled with variants of the Navier-Stokes equation to obtain a description of the dense flow [20]. Discrete particle methods, however, are computationally expensive.

An alternative way is to model the dense particle laden flow as a continuum [5], using a multiphase computational fluid dynamics (CFD) approach. In these approaches, one of the big challenges lie in correctly obtaining the constitutive relations for the modelling of two-phase flows [26]. Concepts from kinetic theory [11] has been used to obtain constitutive relations for certain particle laden flows [15], but has of yet not been applied to highly fluidized beds, or highly turbulent sand laden flows [19]. Continuum models also have the conceptual difficulty of simulating discrete granular effects, such as particle segregation [6].

It is beyond the scope of this paper to give a full survey of the available approaches for the modelling of particle collisions. Readers interested in discrete particle modelling are referred to [6]. For a detailed review of multiphase CFD, see [4, 26]. The goal of this paper is to extend a recently developed numerical framework, the lumped particle model originally presented in [1], with a new hybrid continuum-particle model for particle collisions.

The lumped particle model is a flexible and numerically efficient framework for the modelling of particle transport in fluid flow, that takes into account fundamental features of particle flow, including advection, diffusion and dispersion of the particles. This framework reproduces particle flow properties inherent in both continuum and discrete approaches, and correctly reproduces advection and diffusion phenomena as special cases [1]. There are, however, some particle flow features not included in the framework. Currently, the lumped particle model is applicable to dilute particle laden flows only. In this paper, we want to expand the framework to dense particle flows. When the local volume fraction of particles increases, it is no longer reasonable to ignore inter-particle