Chapter 3
Kinetic Theory for Granular Materials:
Polydispersity

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ABSTRACT

Kinetic-theory-based models of rapid, polydisperse, solids flows are essential for the prediction of a wide range of practical flows found in both nature and industry. In this work, existing models for granular flows are critically compared by considering the techniques used for their derivation and the expected implications of those techniques. The driving forces for species segregation, as predicted by kinetic theory models, are then reviewed. Although the rigor associated with the development of such models has improved considerably in the recent past, a systematic assessment of model validity and computational efficiency is still needed. Finally, a rigorous extension of such models to gas-solids flows is discussed.

INTRODUCTION

In nature and industry alike, flows involving solid particles are time and again polydisperse – i.e., the particles differ in size and/or material density. This polydispersity may (i) be a property of the starting material itself, (ii) arise from the need for two different materials in a processing step, or, (iii) be specified in order to improve system performance. Industrial and natural examples of (i) include coal feedstock to combustors and terrestrial and lunar soils, respectively. The production of titania is an example of (ii), where one step of the synthesis involves both titianium ore and coke, which vary in both particle size and material density from one another. Finally, as an example of (iii), the addition of fines to a relatively monodisperse material has been shown to decrease attrition in high-speed conveying lines (Knowlton, Carson, Klinzing, & Yang, 1994), increase conversion in high-velocity, fluidized-bed

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reactors (Pell & Jordan, 1988) and improve heat transfer efficiency in a circulating fluidized bed (CFB) combustor (Lee, 1997).

Not surprisingly, the flow behavior of a polydisperse material is different from that of its monodisperse counterpart. For example, recall from the previous chapter that a continuum description of rapidly-flowing, monodisperse solids flows is possible via a kinetic-theory analogy, which requires the specification of constitutive quantities such as the solid-phase stress. Similar descriptions are possible for polydisperse flows, though the solid-phase stress, as well as the other constitutive quantities, now also depend on the characteristics of the polydisperse distribution – e.g., the diameter ratio of particles in a binary size distribution, the density ratio of two unlike materials, the standard deviation of a continuous size distribution, etc.

Beyond the aforementioned expected changes to the constitutive quantities caused by polydispersity, such flows also display a counter-intuitive phenomenon which has no monodisperse counterpart: species segregation or de-mixing. For example, agitation of polydisperse solids via vibration, free-fall, or flow down an incline leads to segregation among unlike particles. A famous example of this behavior is the well-known Brazil nut problem, in which a can of mixed nuts, after shaking up and down, is opened only to find an over-representation of the Brazil (large) nuts at the top of the can (Rosato, Prinze, Standburg, & Swendsen, 1987). Although such segregation may be beneficial to operations targeting separation, as found in the mining industry, it may prove detrimental if a well-mixed system is desired, as is common in the pharmaceutical industry. More specifically, consider a tablet which is made from two powder substances – the medication and the binder which holds the medication together. If these two substances are not-well mixed prior to tablet formation, a patient may be over- or under-medicated. A related example with less serious ramifications involves raisin bran cereals, in which the raisins are poured on top of the box prior to loading on distribution trucks since the vibration during transport mixes the raisins throughout the box.

Generally speaking, a predictive understanding of polydispersity and the related segregation phenomenon remains a challenging task, as has been highlighted in several recent review articles and perspectives (Curtis & van Wachem, 2004; Muzzio, Shinbrot, & Glasser, 2002; Ottino & Khakhar, 2000; Sundaresan, 2001). In this chapter, the focus will be on the *rapid* flow of polydisperse solids, in which the contacts between particles are approximated as instantaneous and binary in nature. (Such flows are equivalently referred to as granular gases, collision-dominated flows, high-Stokes flows, or massive-particle flows in the literature.) The scope here will be further limited to continuum descriptions of such flows, which are accordingly based on an analogy with the kinetic theory of molecular gases. The foundation for such models, namely the kinetic equation (Boltzmann or Enskog, as detailed below), can be solved using analytical or numerical methods. In this chapter, the former, which are commonly referred to as "kinetic theory models", will be discussed. In a subsequent chapter, a numerical method known as DQMOM, or discrete quadrature method of moments, will be covered. (For purposes of clarity, it is worthwhile to note that "kinetic theory models" referred to in this manner is common in the engineering literature, whereas the physics community uses the term "kinetic theory" to refer to the starting kinetic equation.)

In sum, the objective of this chapter is provide a critical review of existing kinetic-theory-based models for polydisperse systems, as well as an outlook for future work. It is worthwhile to note that this review is focused on differences in the derivation process itself, rather than a direct comparison of the models with data. The latter, albeit a valuable next step, is beyond the scope of the current effort due to the high degree of complexity associated with the various models (as even a tabulation of the governing equations and constitutive relations for all of the existing models would more than double the length of

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