Lateral diffusive migration of massive particles in high-velocity vertical pipe flow of moderately dense gas-solid suspensions

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Transport processes involved in a gas-particle flow, comprised of spherical particles with a narrow size distribution suspended in a turbulent gas, are investigated theoretically on the basis of the recently developed Enskog theory for multicomponent dense mixtures of slightly smooth inelastic spherical particles [P. Zamankhan, Phys. Rev. E **52**, 4877 (1995)]. The generalized Boltzmann equation of the previous work is modified to incorporate the relevant forces exerted upon individual particles including the drag force by the relative gas motion. Extending the method of moments of Grad [Commun. Pure Appl. Math. **2**, 331 (1949)], the modified Boltzmann equation is solved to obtain the nonequilibrium velocity distribution function for particles of each size. By taking the monodisperse limit, a basic equation is derived for the treatment of the problem of lateral diffusive migration of solids in an assembly composed of separate equisized spherical particles traveling in a fully developed, turbulent upward flow of a gas within a vertical pipe. At moderately high solid concentrations, where the random component of the particle velocity is generated mainly by particle-particle collisions, the particle diffusivity and the thermal diffusion coefficient are found to increase with the square root of the granular temperature, a term that measures the energy of the random motion of the particles.
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I. INTRODUCTION

During the past few years, the hydrodynamics of confined gaseous suspensions has received considerable attention due to its importance in several applications, including fluid catalytic cracking [1] and combustion of low-grade coal in power generation plants [2]. In observing the transport of moderately dense gas solid particles in vertical pipes, where the solid volume fraction is much larger than 0.001, it has been noted [3] that solid particles were distributed nonuniformly over the cross section and that the recirculation of particles occurred against the direction of their net flow. These phenomena clearly influence the particle residence time distribution in the risers, which is important in predicting the behavior of systems in which the particles catalyze reactions between species in the gas or in which they react with the gas.

Several approaches towards developing two-fluid models, in which the gas and the particle phases are treated as a mixture of continua, have been used in an effort to predict the aforementioned observations. The results of the earliest approach, used by Berker and Tulig [4], demonstrated that for the pipe flow regimes relevant to high-velocity gas fluidized beds (6–9 m/s), the particle-eddy interactions tend to move particles laterally due to the presence of a turbulence gradient. As a result of this motion, an uneven distribution of particles over the cross section may appear. The essential approximation in their approach is that the particle collision time τ_c, which characterizes the mean time between successive collisions of a particle, is much larger than the particle viscous relaxation time τ_d, which describes the response of a particle to the drag force created by turbulent fluctuating velocity of the surrounding gas.

Under the operating conditions used for gas fluidized beds, there are many parameters that affect the motion of suspended solid particles relative to a turbulent carrier fluid, including particle inertia and solids loading. For moderately concentrated particle loadings, recent tests [5] indicated that in high-gas-velocity flows, large-scale solid structures (clusters) [3,6], which may be observed at lower velocities with the same rate of transport of solid, give way to a population composed of separate particles whose free and independent motions resemble that of gas molecules in a dense gas in thermal equilibrium. Thus, for this case there is some justification for assuming that the particle collision time τ_c is much smaller than the particle viscous relaxation time τ_d. Under such circumstances the flow regime is not fluid dominated; instead, the frequency of a single-particle displacements is controlled by the rate of collision with the neighboring solid particles [7]. Hence the study of the lateral diffusive migration of solids in a turbulent upward flow of a gas within a vertical pipe at moderately high solid concentrations, which seems to be a possible cause for the tendency of particles to concentrate in the wall region, requires an essentially different approach from those proposed for particle-laden turbulent flows [8].

Developing theories based on the kinetic theory of dense gases [9] to obtain continuum equations for the mass, momentum, and energy of the solid phase, therefore, could

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