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Boundary-element method simulation of the impact of bounding walls on the dynamics of a particle group freely moving in a wide-gap Couette flow

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Abstract

In this study, the impact of the bounding walls on the dynamics of a group of neutrally-buoyant identical rigid spheres freely moving at negligible Reynolds numbers in a wide-gap Couette flow, which is important for understanding the particle migrations presented in concentrated suspensions subjected to inhomogeneous shear flows, is simulated by a three-dimensional boundary-element method (BEM) code. The results show that the particle interactions very close to the bounding walls cause the particle group to migrate away from the walls. As the distance of the bounding walls from the group increases, the migration changes direction and the group then move towards the walls. As this distance continues to increase, the migration of the group decreases and beyond a specific distance from the bounding walls the migration of the group is negligible. In addition, the BEM simulations show that the extent and rate of the migration of the group increase as the inter-particle distance decreases.

Keywords: Boundary-element method; Particle migration; Wide-gap Couette flow; Bounding wall; Inhomogeneous shear flow

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1. Introduction

Simple fluids can be characterized by bulk measurements in linear shear fields. This characterization allows the prediction of behavior in non-linear shear fields. On the other hand, the behavior of suspension in non-linear shear fields cannot be predicted by the results for linear shear fields. Most analytical approaches to suspension flow problems use degenerate micro-scale models of local particle configurations to determine macroscopic quantities (see e.g. [1–5]). Under this approach, the primary effects are calculated from analytically tractable hydrodynamic interactions between a small number of particles. The results obtained provide a rational vehicle for deriving the macroscopic properties of suspensions, at least in the dilute particle limit. Nevertheless, work on the hydrodynamic interaction between multiple particles suspended in nonlinear shear field is rare. The only such work so far, to the best of our knowledge, is that of Haber and Brenner [6] who investigated analytically the hydrodynamic interaction between two particles suspended in a nonlinear shear flow by the method-of-reflection approximation, providing an insight into the influence of nonlinear shear fields on particle motions and interaction in the dilute limit.

As analytical solutions of the multi-body Stokes-flow problem are currently intractable, numerical simulations have been widely used to analyze multi-particle hydrodynamic interactions. Notable among the numerical methods are Stokesian dynamics, which is limited to linear flow fields (see e.g. [7–12]), boundary-element method (see e.g. [13–17]), and multipole method (see e.g. [18–20]).

It is now well established that neutrally-buoyant particles migrate from the higher shear-rate regions to lower ones in a concentrated suspension subjected to inhomogeneous shear-flow (see e.g. [21,22]). All these experimental results are under the influence of the bounding walls as the suspensions were in closed containers. However, diffusive flux models of this phenomena assume that the particle migration is driven by gradients in shear-rate and viscosity (see e.g. [23]).

In this paper, we subject a group of particles to identical inhomogeneous shear fields in wide-gap Couette flows and vary the distance to the outer bounding walls and conduct dynamic simulations using a three-dimensional boundary-element method (BEM) code. We first present the problem addressed and its mathematical description in Section 2, along with a brief description of the BEM solution technique used. In Section 3, the accuracy of the BEM simulations is benchmarked with the available exact solutions for two identical neutrally-buoyant smooth spheres suspended in a simple shear flow [2]. The impact of the bounding walls on the dynamics of the particle group, consisting of five identical neutrally-buoyant rigid spheres, is simulated by the BEM code in Section 4. Finally, conclusions are summarized in Section 5.

2. Statement of the problem and simulation technique

2.1. Problem addressed

The physical system under consideration is shown schematically in Fig. 1, where a group of 5 identical neutrally buoyant rigid spheres are freely moving at negligible Reynolds numbers in a wide-gap Couette flow. The particle group is near the outer bounding wall of the Couette device, which has a dimensionless height of $H/R_{\mathrm{i}} = 2$, where R_{i} is the radius of the inner cylinder which rotates at the angular velocity $\omega = 0.1$ radians per sec-