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Stabilization of concentration waves in fluidized beds of magnetic particles

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In this work, a linear stability analysis is carried out to evaluate the behavior of concentration waves in polarized fluidized beds. The magnetic effects are taken into account by the addition of a magnetic stress tensor on the particulate phase stress tensor. A non-linear model is proposed for the fluid–particle interaction force, so that the inertial effects arising from the wakes behind the particles are incorporated. We see that the alignment of the magnetic particles with the magnetic field stabilizes the fluidized bed flow and the efficiency of this stabilization is maximum when the field lines are parallel to the fluidization direction. The results are in qualitative agreement with experiments. The interaction of the magnetized particles with an external magnetic field produce a stronger stabilization of linear instabilities in fluidized beds than the one induced by particle pressure, associated with velocity fluctuations and collision of the particles, and by the interaction of the wakes of the particles, associated with the inertia of the flow. All three effects act in the sense of stabilizing fluidized beds against concentration waves.

1. Introduction

The process of fluidization occurs when a static bed of solid particles is suspended by an upward flow of gas or liquid. As the flow rate increases, the drag acting on the particles increases up to a point in which it balances the net weight of the particles. A further increase on the flow rate will provoke an expansion of the bed, generating a configuration of mobile particles suspended in a region of the reservoir called fluidized bed.

The study of the stability of suspensions, specially in fluidized beds, aims to identify the hydrodynamical mechanisms that cause the appearance of bubbles in these flows. Bubbles are large regions void of particles that travel upstream and alter significantly the pattern of the flow. Therefore, it is extremely important to identify the mechanisms behind bubble formation in order to be able to better understand and control such flows. A review article [1] has reported the current understanding of the various stages of bubble evolution in liquid and gas-fluidized beds.

When restricted to a one-dimensional geometry, fluidized beds show a configuration in which concentration waves propagate along the system, as observed in Fig. 1, and it is believed that they are at the origin of the formation of bubbles, but the connecting link is still missing [1–4]. Several works have tried to shed some light into this problem and study voidage-wave instabilities and bubble formation in liquid and gas-fluidized beds, either using two-fluid models [4], experiments [5,6] or a combination of experiments of particle image velocimetry and numerical simulations based on discrete element method [7]. Recently, the growth rates of secondary instabilities in two-dimensional fluidized beds have been investigated with stratified fluids in order to explore the dynamics of gravitational overturning in these suspensions [8].

Experimental observations [9] indicate that fluidized beds composed of magnetic particles in bubbling condition can be stabilized to a particulate fluidization regime when a magnetic field is applied parallel to the direction of fluidization. This behavior was partially explained by continuum models of multiphase flows, that indicate an inhibition on the formation of irreversible aggregates in the fluidized bed linked to the presence of magnetic forces acting on the particulate phase [9,10]. More recently, a theoretical study based on Lattice Boltzmann numerical simulations has proposed a Eulerian–Lagrangian numerical description of a two-dimensional liquid–solid fluidized bed with a uniform magnetic field [11]. The authors have shown that the expansion of a fluidized bed is strongly influenced by the mechanism of formation of straight long chains of particles under the presence of an applied external field. Nevertheless, these studies have not examined neither the wake effects during particles interactions, studied in detail in the experiments in [12], nor the configurations in which the magnetic field is applied in non-parallel directions with respect to the fluidization, as in the

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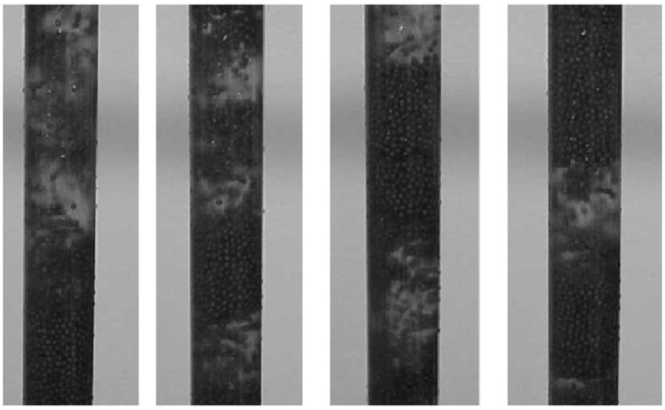

Fig. 1. A typical sequence of one-dimensional concentration waves propagating in a liquid fluidized bed. The particles are made of steel and the fluidizing fluid is water. From left to right, once clearly observes the propagation of a region of high concentration of particles moving upwards. The visualizations were carried out in the Fluid Mechanics Lab — VORTEX at the University of Brasilia — Brazil.

experiments in [13]. As a first step towards model development and experimental observations in the field of magnetic field assisted fluidization, a general dimensional analysis and scaling study has been conducted for this kind of particulate system in [14,15]. The relevant concept of an effective elastic moduli of a deformable medium, whose behavior can be controlled by an external magnetic field, was also examined in the context of gas–solid fluidized bed instabilities [16].

In [17], a formulation that indicates stabilization of fluidized bed for arbitrary direction of the applied field was developed, but it was restricted to fluidizations at low to moderate particle Reynolds number since only viscous forces in the fluid–particle interaction force were considered. In this work, an extension of the model presented in [17] is examined. This model considers the inertia of the fluid on the fluid–particle interaction force, by introducing a nonlinear term based on the Ergun correlation [18], initially established empirically for concentrated fixed beds. A more detailed discussion about the modelling of the fluid–particle interaction force, as well as aspects of the particle–particle interactions in the fluidized bed context, can be found in [2,4,6,19] and in the references therein.

The results show that, even for large particle Reynolds number, the presence of a magnetic field stabilizes a fluidized bed of magnetic particles and that there is a significant stabilization of the flow for other orientations of the applied field. Nevertheless, the stabilization is maximum when the applied field is parallel to the direction of fluidization and is virtually non-existent when the field is applied perpendicular to the flow. These theoretical results are in qualitatively agreement with the experimental observations presented in [13–15].

2. Balance equations of the particulate flow

The mathematical model we use in this work is based on the hypothesis that both the fluid and the fluidized particles are interpenetrating continua [4,17] and, therefore, governing conservation equations can be written in terms of local mean properties, defined over sensitive volumes that are sufficiently large to contain a significant sample of particles, but sufficiently small when compared to the size of the system [3].

The continuity equations for the fluid and the particulate phase, both considered incompressible, are written as [3]:

$$\frac{\partial \epsilon}{\partial t} + \nabla\cdot\left(\epsilon \mathbf{u}\right) = 0 \quad \text{e} \quad \frac{\partial \phi}{\partial t} + \nabla\cdot(\phi \mathbf{v}) = 0, \tag{1}$$

respectively. In these equations, ϵ represents the local void fraction of the flow and $\phi = 1 - \epsilon$ denotes the local volume concentration of the particles. The local mean velocity of the fluid phase is $\mathbf{u}$, and the velocity of the particulate phase in given by $\mathbf{v}$.

Similarly, the equations of motion for each phase are obtained in the following form:

$$\frac{\partial}{\partial t}\left(\epsilon \rho_f \mathbf{u}\right) + \nabla\cdot\left(\epsilon \rho_f \mathbf{u}\mathbf{u}\right) = \nabla\cdot\left(\epsilon \mathbf{T}_f\right) - \mathbf{f} + \epsilon \rho_f \mathbf{g}, \tag{2}$$

$$\frac{\partial}{\partial t}\left(\phi \rho_p \mathbf{v}\right) + \nabla\cdot\left(\phi \rho_p \mathbf{v}\mathbf{v}\right) = \nabla\cdot\left(\phi \mathbf{T}_p\right) + \mathbf{f} + \phi \rho_p \mathbf{g}, \tag{3}$$

in which ρ_f and ρ_p represent the specific masses of the fluid and particulate phases, respectively, and $\mathbf{g}$ represents the acceleration of gravity. In these equations, we identify three terms for which closure models have to be proposed: the average stress tensors for the fluid, $\epsilon\mathbf{T}_f$, and for the particulate, $\phi\mathbf{T}_p$, phases, and the fluid particle interaction force, $\mathbf{f}$.

3. Constitutive equations

For the fluid phase, the classical linear stress tensor for a Newtonian fluid is proposed, in terms of local mean variables:

$$\epsilon \mathbf{T}_f = -p\mathbf{I} + \mu_f\left[\nabla \mathbf{u} + \nabla^T \mathbf{u} - \frac{2}{3}(\nabla\cdot\mathbf{u})\mathbf{I}\right]. \tag{4}$$

In Eq. (4), p represents the local mean mechanical pressure of the fluid phase and μ_f denotes the dynamical viscosity of the fluid. Despite the progress that was made to understand the fluid–particle [19] and particle–particle [20] interaction mechanisms in the particulate phase, there are still many controversies in the literature about the physical credibility of closure models for the two-fluid model, mainly with respect to the model of the stress tensor of the particulate phase [2,4,6,10]. We consider the standard model similar to Eq. (4), in which stresses are linked to a particle pressure and to a particle viscosity, both quantities being related to the transport of momentum by velocity fluctuations of the particles. The former is related to $\frac{1}{3}\overline{v_i' v_i'}$ (summation convention implied), where v_i' represents the components of the velocity fluctuations of the particles $\mathbf{v}'$ around an average velocity $\overline{\mathbf{v}}$. The second is associated to the dissipation of energy in the particulate phase, i.e. it is related to the tensor $\overline{v_i' v_j'}$, with $i \neq j$, and also to the viscous resistance to changes in the relative configuration of the particles [2]. Furthermore, the magnetic effects will be considered separately in an additional constitutive term in the formulation of the stress tensor of the particulate phase. Therefore, based on this comments, we propose the following expression for $\phi\mathbf{T}_p$:

$$\phi \mathbf{T}_p = -p_p(\phi)\mathbf{I} + \mu_p(\phi)\left[\nabla \mathbf{v} + \nabla^T \mathbf{v} - \frac{2}{3}(\nabla\cdot\mathbf{v})\mathbf{I}\right] + \mathbf{T}_m, \tag{5}$$