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Characterization of a sediment layer of concentrated fluid-solid mixtures in tilted ducts at low Reynolds numbers

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ABSTRACT

In this paper we use a continuum mixture model to solve numerically the momentum and continuity equations associated with the sedimentation dynamics of highly concentrated fluid-solid mixtures in tilted ducts at low Reynolds numbers. The set of numerical simulations include several combinations of fluid viscosity, duct angle and solid concentration of particles. This research aims to show the phenomenology and dynamics associated with the sedimentation of monodisperse particles under different physical conditions and the characterization of the final stage of the sediment layer in two kinds of inclined geometries, with and without a horizontal section. Using scaling arguments, a mathematical expression formed by three dimensionless groups including the inertial number, particle concentration and the ratio between the sedimentation Grashof number to the Reynolds number is proposed to explain the height of the sediment layer in the slope change zone of a duct. Additionally, we have found that the initial particle concentration is a very relevant variable for knowing under what conditions the duct could get obstructed. In combination with some system angles, they might represent a risk of duct plug. Imposing a condition of obstruction, we have found dimensionless parameters that result in the blockage of the duct in the slope change zone. The results can be applied in the transport of fluid-solid mixtures and, in the engineering design of ducts with abrupt slope changes.

1. Introduction

The hydraulic transport of solids at high concentrations (e.g., ore concentrates and tailings) is a widely used technique in the mining and dredging industry. Normally, such method is carried out mixing the particles with water in order to enable the motion of the solid phase through pipelines and ducts [1]. This technology has been proven to be a cost-effective option for long distances and high throughput requirements. In the particular case of ore concentrates, pipelines can be as large as hundreds of kilometres long, and are commonly installed in natural topographies, which include the presence of low and high points. The design of this kind of infrastructure faces challenges including the need to keep solids in motion at all times [2] and to enable safe system startups after planned shutdowns or power outages. When the latter operational scenario occurs, it is required during startup to remove the solids settled at high concentrations at the various low points in the system. The frictional resistance to motion in those points, where solids have settled and compacted, is higher than that corresponding to steady operation [3], and requires to be accounted for when selecting both pipeline and pumping equipment. Failure to cope with proper designs in long distance pipelines may cause ruptures due to blockages, thus affecting urban centers or natural resources such as lakes, rivers, and agriculture, potentially causing severe environmental problems and enormous damage to local communities [1,2,4]. Central to this point is the need to properly address the implications of high and low points through the development of engineering models for solids migration

Sedimentation is the process by which solid particles immersed in a fluid are deposited at the bottom by the action of gravity. Sedimentation is one of the oldest known techniques used in industry to clean fluids or, alternatively, to recover particles from suspensions [5]. In 1920, Boycott noted that certain blood corpuscles settled faster at the bottom in inclined test tubes than in test tubes that were in an upright position. This improvement in the sedimentation velocity is

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due to that in an inclined duct, the suspension has a short distance to reach the lower side of the duct, before they start to slide down to the bottom of the duct, whereas in a upright duct all the sediment is slow and there is no vertically rapid sliding [6,7].

For almost five decades the behaviour of inclined settlers was described using a kinematic model called PNK in recognition of Ponder [8] and Nakamura & Kuroda [9] who developed it. A typical phenomenon observed in inclined settlers for laminar flow is displayed in Fig. 1. The PNK model states that the production rate of clear fluid per unit depth of a rectangular settler is given by $S = w_0F[\cos\theta + H\tan\theta/b]$, where w_0 is the sedimentation velocity of a particle, F is a hindered function which accounts for the interaction of many particles immersed in a fluid, θ is the angle of inclination of the system, H is the instantaneous height of the suspension and b is the space between the walls of the duct. PNK theory often overestimates the efficiency of an inclined settler, however it does not consider the dynamics of fluid movement as it is based solely on a mass balance [10]. When a settler is inclined, a thin layer of clear fluid is formed along the upper wall. Due to the density of the fluid being less than the density of the suspension in the vicinity, a force is experienced which causes the fluid to accelerate upwards [11].

Resistance to this upward movement is given by the viscous and inertial forces acting within the clear fluid layer as well as the upper wall of the settler and regions of particle suspension. If the velocities within the layer of clear fluid are very large, it might be possible that waves appear along the interface between the suspension region and the clear fluid layer. These waves can grow and break as they ascend to the settler, thus dragging the suspension to the clear fluid layer and decreasing the efficiency of the settler [12]. In order to predict the performance of an inclined settler, it is necessary to describe the formation and growth of these instabilities.

Works related to the dynamics of suspensions in tilted settlers in the decade preceding ninety, can be found in Davis & Acrivos [13]. Current analytical theories to describe the dynamics of suspensions in tilted ducts are generally based on the analysis presented by Acrivos & Herbolzheimer [10], who studied the process using a simplified model. The equations used consist of a continuity equation for each phase, i.e., one for the solid phase and one for the fluid phase, an equation of momentum mixture describing the suspension of particles as a whole and a relationship between the velocities of each phase. Neglecting inertial effects and assuming that the suspension region has a uniform concentration of solids, these authors used boundary layer analysis to find expressions for the geometry and flow within the clear fluid layer. In addition, they determined that the kinematics of the sedimentation process is described by two dimensionless groups, a sedimentation Reynolds number and quotient of a settler Grashof and Reynolds number, which are given by $Re = Hw_0F\rho_f/\eta_f$ and $\Lambda = H^2g(\rho_s - \rho_f)\phi/\eta_f w_0 F$, respectively. In this expression, ϕ is the volume fraction of particles in the suspension zone. The hypothesis of negligible inertial forces established in the work of these authors implies that the analysis is limited to the settlers where $\Lambda \gg 1$ and $Re\Lambda^{-1/3} \ll 1$.

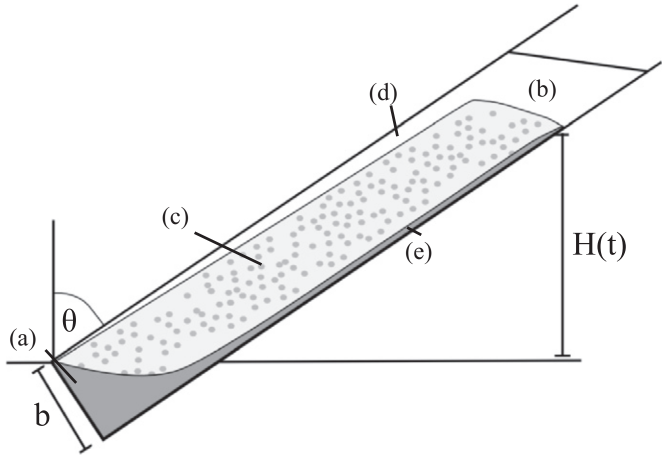

Fig. 1. Schematic of the conceptual model: (a) Sediment bed, (b) Clear fluid region, (c) Suspension region, (d) Clear fluid region and (e) Sediment layer.

Finally, they found that the rate of production of clear fluid would be predicted by the theory PNK whenever the interface between the suspension region and the clear fluid layer remains stable and $\Lambda \to \infty$. Herbolzheimer [12] developed this analysis to settlers under viscous conditions ($Re\Lambda^{-1/3}$) and he compared his theoretical results with experimental results of instability waves on the interface. Later, Shaqfeh & Acrivos [14] included inertial effects and extended the theory for all values of $Re\Lambda^{-1/3}$. Comparisons between experimental and analytical results for the clear fluid layer predicted by this theory have been very satisfactory, particularly for the more viscous cases where $Re\Lambda^{-1/3}$ is small. In this paper we have used a continuum mixture model to solve numerically the momentum and continuity equations associated with the sedimentation dynamics of high concentrated fluid-solid mixtures in tilted ducts. While previous works were able to describe the operation of settlers when the interface of clear fluid layer is stable, they do not define under what kind of conditions this occurs. Acrivos and other researchers have applied linear stability theory to the region surrounding the clear fluid layer to find conditions under which small perturbations in the interface will grow over time. Subsequently, Nir & Acrivos [15] did experiments on inclined surfaces and found that for given values of the concentration of particles in the suspension, the sediment flow remained constant only if the angle of the system exceeded a minimum value. Additionally, a discontinuity in the concentration of particles in the suspension was found. Afterwards, Kapoor & Acrivos [16] implemented the model proposed by Nir & Acrivos [15] but including the effects of shear-induced diffusion due to gradients in the shear stress likewise the slip velocity along the walls of the duct. The focus of this research is on the nonlinear dynamics associated with the migration of particles at low slopes, and in particular the consequences for axial transport of solid material under these conditions, with emphasis on the conditions for the generation of obstructions at high particle fractions. In Section 2, we provide the mathematical model used for our numerical simulations, and the numerical procedure used in our calculations. In Section 3, the results of our numerical simulations are presented and discussed. Finally, the conclusions are showed in Section 4.

2. Governing equations

A set of numerical simulations has been made using COMSOL Multiphysics with the CFD package for modelling the sedimentation of particles in tilted ducts [17,18]. The dynamics of a suspension can be modelled by two equations of momentum transfer, one for particles and the other for the fluid, plus a continuity equation for both phases. Assuming that the mass transfer between the two phases is zero, the continuity equations for the continuous and dispersed phase are, respectively, $\partial_t(\rho_f\phi_f) + \nabla\cdot(\rho_f\phi_f\mathbf{u}_f) = 0$ and $\partial_t(\rho_s\phi_s) + \nabla\cdot(\rho_s\phi_s\mathbf{u}_s) = 0$, where ϕ is the volume concentration, ρ is the density and $\mathbf{u}$ is the velocity. The subscripts f and s refer to quantities associated with the continuous phase (fluid) and the dispersed phase (particles). In this model, both the continuous and the dispersed phase are considered incompressible. Therefore, the above equations can be simplified as,

$$\frac{\partial\phi_f}{\partial t} + \nabla\cdot(\phi_f\mathbf{u}_f) = 0, \tag{1}$$