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Experimental study of sedimentation of concentrated mono-disperse suspensions: Determination of sedimentation modes

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ABSTRACT

The goal of this paper was to experimentally investigate sedimentation of concentrated suspensions of mono-sized particles at low Reynolds number. Experiments were carried out with polymethylmethacrylate (PMMA) spheres of three different radii suspended in a fluid of matched refraction index. Laser Induced Fluorescence technique was used to determine the spatio-temporal evolution of particle concentration and displacement of sedimentation fronts. It was mainly possible to recognize the existence of specific modes that govern the sedimentation process when particle radius is changed. As a consequence, the maximum packing concentration of the sediment was found to be a decreasing function of particle radius and observed results were found to be well correlated with the corresponding Richardson and Zaki flux function.

1. Introduction

Suspensions of solid particles are ubiquitous in environmental field and material engineering processes as solid–fluid separation. It is thus of primary importance to characterize and predict their behavior when they are submitted to external mechanical forces. During the last decade, most attention has been paid to study the behavior of suspensions of mono-sized particles at low Reynolds number. Among processes in which suspensions are involved, the mostly encountered is the sedimentation of weighty hard spheres dispersed in a Newtonian liquid. One of the major issues is to determine the concentration and velocity of particles in the suspension during the process. These ones differ mainly in the chosen configuration: in a concentration process, a continuous supply of particles is set up and the constituted deposit is continuously removed. Alternatively, in batch sedimentation, the suspension is contained in a finite volume and can evolve freely until a state of complete phase separation is reached. In some studies, attention is paid to the early stage of sedimentation process by focusing on time evolution of flow pattern by determining the characteristic length of formed swirls [1].

Besides flow pattern, batch-settling processes of an initially homogenous suspension of mono-sized particles do globally display the same typical topology. During the sedimentation, the suspension exhibits successively from the top to the bottom a clear fluid zone, an intermediate zone where particles are settling and lastly a sediment where particles are at rest and where the solid volume fraction is assumed to be maximum. Kynch [2] proposed a model that describes the sedimentation of an ideal suspension where the flowing suspension is a mixture of identical solid particles of velocity $\vec{v}_S$ and a continuous fluid phase of velocity $\vec{v}_F$. For simplicity, Kynch supposes that the particle concentration is constant in each horizontal section and the problem is then let one-dimensional with the vertical axis z oriented upward and L is the initial total height of the suspension. The local volume fraction of solid $\phi(z,t)$ depends on the space and time variables following continuity equation:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \vec{f}(\phi, t) = 0. \qquad (1)$$

In this equation, $\vec{f}(\phi,t) = \phi \vec{v}_S$ is the absolute density flux of solid and it holds only in intervals where ϕ and velocities are continuous functions. Such a flux density function describes how settling particle velocity is affected by its neighbors and must have an existence domain restricted to the possible volume fractions $[0;\phi^*]$ with ϕ^* being the sediment compacity. In this interval, f is definite negative and is zero at $\phi = 0$ and $\phi = \phi^*$. To completely describe the sedimentation process, an "exact" form of $\vec{f}$ at intermediate ϕ is needed. Several empiric forms of flux density function have been proposed in literature and many of them consist in writing the actual solid velocity v_S as velocity of isolated hard sphere V_S (Stokes velocity) hindered by other particles [3–6]. An extensive review of popular formula was proposed by Blazejewski [7]. The effective-medium approaches can predict the transport properties of suspensions. Koo [8] recently compared four effective-medium models which mainly differ in the distance from a test particle beyond which the

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suspension has an effective viscosity. He found that one of them (EM IV in his paper) does effectively very well agree with experimental viscosity data up to $\phi = 0.45$. One of the most popular approach which well predicts the settling velocity of suspension is the Richardson and Zaki relationship ($f = \phi V_S(1-\phi)^n$) with n = 4.65 for creeping regime (Reynolds number Re < 0.2) [9]. In any case and to conform the experimentally observed behavior, one should choose a flux density function with at least one inflection point that satisfies the sign of derivatives at the ϕ interval limits.

By solving the continuity Eq. (1) for a uniform initial concentration ϕ_0 together with the boundary conditions one can get the temporal evolution of the local solid volume fraction and its corresponding local velocity. The plot of iso-concentration lines in a z–t frame defines the sedimentation mode and describes the way that the considered suspension follows during sedimentation depending on considered conditions (see below).

As theoretical aspects of sedimentation of concentrated suspensions are well documented, only scanty experimental results dealing with sedimentation modes are unfortunately available in literature. So, to probe such sedimentation processes, the commonly used techniques rely on wave propagation in dense media as X-ray [10], γ-ray [11,12] or Ultrasonic Doppler Velocimetry techniques [13]. They basically allow the determination of local velocity and/or local concentration and which sensitiveness determines the refinement of experimental data. In that respect, Laser Induced Fluorescence (LIF), a noninvasive technique based on light propagation in the moving suspension, has been recently reported to be the most suitable one to measure local change of solid concentration [14]. The principal advantage of this method is that only labeled particles do respond to excitation wave allowing high resolution of local change of particle concentration and displacement especially at high solid fraction.

So, the aim of the present contribution is to deeply probe sedimentation of mono-sized concentrated suspensions and examine how concentration and velocity of particles are affected by the particle size in a settling suspension. Before that, we briefly summarize in the following section the seven possible modes that a settling suspension may follow as reported in literature. In the remaining sections, we successively present materials, the LIF technique and how crude data are exploited to extract the relevant physical quantities before presenting and discussing the obtained results.

2. Sedimentation modes

To construct a solution of the problem presented here above (Eq. (1)), it is firstly necessary to simultaneously solve at t = 0 two Riemann's problems [15]. Each solution may be a shock line or a rarefaction wave [6] that emanates from z = 0 and z = L. A shock line corresponds to a discontinuity of solid fraction while for a rarefaction wave the concentration continuously evolves.

If the density flux function presents one or two inflection points, the graphical intersection of these solutions does consequently occur between two straight lines or between a straight line and a rarefaction wave and such intersection produces a line that may be curved or not. Out of discontinuity regions, $\phi(z,t)$ is a continuous function and the use of the method of characteristics shows the problem's solution to be constituted of linear functions z = z(t) on which ϕ is a constant (iso-concentration lines). More details on the resolution method can be found in early published works dealing specifically with theoretical aspects [5,16–18]. In any case, seven sedimentation modes (*MS*) are then reported to may be a priori encountered for mono-sized suspensions depending on initial conditions and the precise form of the density flux function $f(\phi)$ [18,19,25]. The sedimentation modes we are dealing with in this paper and labeled *MS-1* to *MS-5* are displayed in Fig. 1. For each mode are drawn iso-concentration lines which slope is graphically determined from the $f(\phi)$ plot. All of these sedimentation modes obviously end at $t = t_c$ by a stationary state that is characterized by a sediment of compacity ϕ^* and whose height is $z_c = \phi_0 L / \phi^*$. For the most simple mode *MS-1*, the interfaces S_1 and S_2 are shocks that represent respectively the concentration jumps between 0 and ϕ_0 and between ϕ_0 and ϕ^*. Both of these shocks end at the critical time t_c beyond which only a clear fluid–sediment interface S_3 does survive. For modes *MS-2* to *MS-5*, the rising shock S_2 disappears leaving a rarefaction wave R_1. The difference between these modes corresponds to the presence or not of a discontinuity alternatively between the rarefaction wave and the suspension at ϕ_0 and between the rarefaction wave and the sediment at ϕ^*.

So, from what is briefly exposed here above one can see that the precise process of sedimentation of a suspension should depend on particle radius, the initial solid volume fraction and the correction of isolated Stokes velocity that determines the precise form of the density flux function.

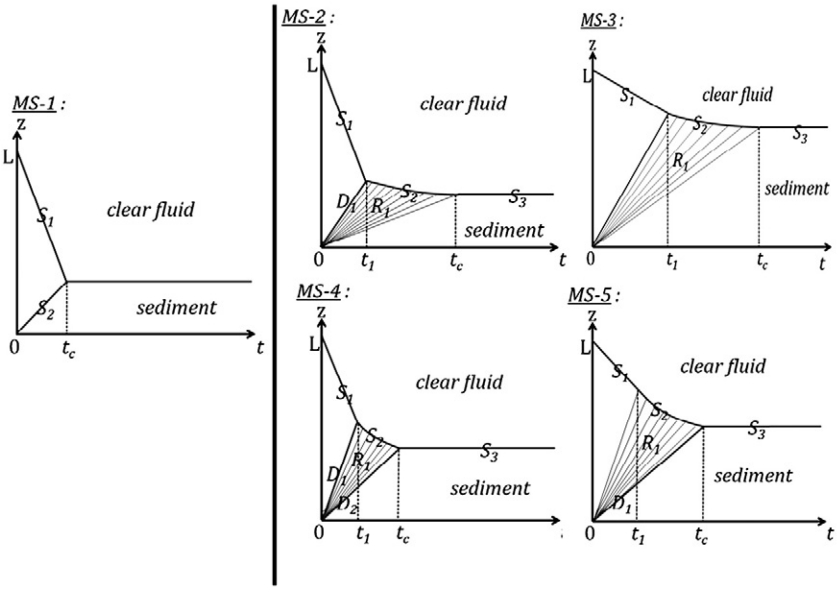

Fig. 1. Sedimentation modes *MS-1* to *MS-7*. Thin lines R_i are iso-concentration lines in rarefaction waves, thick lines represent shock line S_i or discontinuity D_i.