Journal of Non-Newtonian Fluid Mechanics 229 (2016) 79–85

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: www.elsevier.com/locate/jnnfm

Topological transitions in unconfined vibrated concentrated suspensions

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ARTICLE INFO

Article history:
Received 20 August 2015
Revised 13 January 2016
Accepted 19 January 2016
Available online 29 January 2016

Keywords:
Concentrated suspension
Vibration
Jamming

ABSTRACT

Vertical vibration of a concentrated suspension of spherical particles in a liquid yields an array of intriguing behaviors. Here we report new results for unconfined suspensions on a vibrating plate, and show that under certain conditions the suspension forms depressions or craters, while in other conditions it gathers to form a mound, a conical "volcano", or even a sphere that sits just above the vibrating plate. This behavior results from a jamming transition as the plate accelerates upward, followed by unjamming as it accelerates downward. The ability of periodic jamming and unjamming to induce topological transitions is confirmed by scaling analysis, and sphere formation is further examined by numerical simulation of a suspension with an acceleration-dependent viscosity.

1. Introduction

Concentrated suspensions of particles saturated with a liquid are common in nature and industrial applications, being found in materials as diverse as saturated soil, printing ink, cement or "drilling mud," and toothpaste. The flow of these materials is intimately connected to their structure, and the mathematical description of this structure-property relationship is still far from complete. Among the many interesting physical manifestations of this relationship are the observations of "jamming," or sudden cessation of flow, as well as yielding, or sudden onset of flow. Mechanical vibrations such as those found in earthquakes, piezoelectric inkjet printers, and drilling operations, are often present in suspension processing operations [1], or even imposed intentionally [2], and interact with suspension structure and rheology in ways that are not understood. In this paper, we report new results for the behavior of vibrated samples of concentrated, non-Brownian, non-neutrally buoyant suspensions of hard spheres.

It is now known that when neutrally-buoyant, hard-sphere suspensions undergo a shear flow, even at volume fractions below the maximum packing fraction, they can exhibit a sudden increase in resistance to flow, known as "discontinuous shear thickening" (DST). The viscosity increase can be several orders of magnitude, and has been observed at low Reynolds numbers and in non-Brownian [3–5] as well as in Brownian suspensions [6,7]. Mari et al. [8] point out that, particularly for non-Brownian spherical particles at low Reynolds number, the presence of such a jamming transition suggests the presence of non-hydrodynamic influences, in the absence of which the rheology is solely determined by the particle volume fraction ϕ. The abruptness of the viscosity divergence at jamming is not captured by numerical simulations even when particle-particle lubrication interactions are included, making it likely that non-hydrodynamic friction alters the formation of hydrodynamic clusters usually associated with shear thickening.

Although most theoretical and experimental work on DST and jamming have focused on shear flows, controlled vibrations of non-neutrally buoyant suspensions provide an alternative path for experimentation. Probing the behavior of fluids in the presence of vibration has a long history, dating at least to the pioneering work of Faraday [9] on wave formation in deep, inviscid fluids perturbed by mechanical vibration. That description has since been expanded significantly, to account for the effects of finite viscosity [10,11], elasticity, and surfactant-laden surfaces [12,13]. Vibrated shallow layers have also been studied, as have the effects of vibration at low Reynolds number [14–16].

When the vibrated fluid has a complex microstructure, its surface exhibits a number of features that are completely different from what might be described as Faraday waves. Merkt et al. [17], Deegan [18] and Falcón et al. [19] showed that suspensions of corn starch particles, emulsion droplets or glass beads form stable holes when vibrated, and it has recently been shown that the holes can be induced to replicate [20]. Schleier-Smith and Stone [21] showed that suspensions of brass spheres exhibited heaping and cracking when vibrated, and a range of patterns in vibrated neutrally-buoyant suspensions are described by von Kann et al. [22]. Wolf et al. [23] subjected viscoplastic Carbopol solutions, often

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http://dx.doi.org/10.1016/j.jnnfm.2016.01.014
0377-0257/

described as packed suspensions of soft polymeric particles [24], to vertical vibration, and found that geometric patterns of holes formed, with the number of holes depending on the vibration frequency.

In this paper we describe new results obtained by imposing controlled, vertical vibration on unconfined samples of concentrated suspensions of glass particles in aqueous solution. The effects of particle diameter, particle volume fraction, the density difference between the particles and suspending fluid, the acceleration, and the frequency are considered. A range of behavior is observed that is distinctly different than what has been reported previously, including, in certain conditions, the formation of a spherical ball of suspension in contact with the vibrating plate at only its lowest point. In addition, it is shown that the transition from one type of behavior to another can be described by using a dimensionless group consisting of a ratio of the time scale for the suspension to sediment to form a jammed layer, to that of the period of the imposed oscillation.

2. Materials and methods

Our suspensions consist of glass spheres of density 2.5 g/cm^3, with average diameters d and standard deviations of 45 ± 8 μm, 217 ± 14 μm, and 376 ± 19 μm (referred to below as 50 μm, 200 μm and 400 μm suspensions, respectively). The particles are dispersed in aqueous solutions containing sodium polytungstate to vary the density (1.0–2.5 g/cm^3). A reflected light microscope (Leica Microsystems GmbH Model DM 2500 M) was used to verify particle sphericity and to determine the average diameter and standard deviation based on random sampling. The solid volume fraction ϕ ranged from $0.50 < \phi < 0.61$, and the density difference $\Delta\rho$ between the glass spheres and the aqueous suspending fluid was in the range $0 < \Delta\rho < 1.5$ g/cm^3.

Vibration was imposed with two different mechanical shakers. A Controlled Vibration Crowson Technology Shaker ED-3 produced accelerations of $5 < \Gamma < 15$, where Γ is the acceleration divided by the gravitational constant g, as monitored by an attached accelerometer (Silicon Designs, Inc., Model 2260-050). An LDS V408 shaker, cooled with an ACI 7MS8 centrifugal fan, provided higher accelerations up to $\Gamma = 100$, as measured by a PCB Piezotronics 353B31 accelerometer. Sinusoidal vibration signals with frequencies f of 60–120 Hz were generated and analyzed using a VT DSO-2810H oscilloscope, spectrum analyzer and signal generator. Measured masses of glass beads and liquid were combined to create an initial sample diameter of 3–4 cm on the Plexiglas plate, which was mounted 5–8 cm above the shaker. To reduce evaporation, the sample was covered with a Plexiglas case large enough not to interfere with its motion.

Experiments were repeated four times at each frequency and volume fraction for the 50 and 200 μm beads and three times at a volume fraction of 0.61 for the 400 μm beads. Seven frequencies and seven volume fractions were studied, evenly spaced in the ranges 60–120 Hz and $0.50 < \phi < 0.61$. One of each of the four sets of experiments for the 50 and 200 μm beads was performed after addition of the non-ionic surfactant polyoxyethylene 10 lauryl ether ($C_{12}E_{10}$) to the aqueous phase. Aliquots of a 5×10^{-5} M $C_{12}E_{10}$ stock solution were added to standardize the surface tension σ of each aqueous phase to 38 mN/m while maintaining densities in the range $1 < \rho < 2.5$ g/cm^3. The critical micelle concentration for $C_{12}E_{10}$ was determined to be 2×10^{-4} M.

3. Results

Several types of physical changes were observed within a few seconds of the imposition of vibration, depending the characteristics of the vibration and the suspension. These phenomena, shown in Fig. 1(a–d), were grouped under the labels “crowns and craters”, “mounds”, “volcanoes” and “spheres”. Crowns refer to a ridged formation at the outer edge of the suspension, reminiscent of the standing crowns reported by Schleier-Smith and Stone [21], but are shallower and have a larger radius. The crater at the center of the sample in Fig. 1a formed spontaneously, and was not induced as was done in previous studies of hole formation [17,18]. Such craters did not traverse the entire depth of the sample, and some convection was visible at the edge. In some cases, the outer edge of the crater grew upwards, forming vertical “fingers,” which after a few seconds collapsed back downward. The mounds, volcanoes and spheres correspond to progressively greater levels of radial contraction by the suspension sample as a consequence of the vibration. As the sample shrinks in its radial dimension, its height grows because the suspension is incompressible.

Starting from low values where no morphological features were observed, the acceleration was gradually increased and threshold values recorded marking the emergence of configurations such as those in Fig. 1. The dependence of these threshold accelerations on frequency f (60–120 Hz, 7 values), particle volume fraction ϕ (0.50–0.61, 8 values), density difference $\Delta\rho$ (0–1.5 g/cm^3, 6 values), and bead diameter (50, 200 and 400 μm) was evaluated, with 3–4 repetitions at each condition studied. The results were then organized into state diagrams.

For particles with diameters of 50 and 200 μm, diagrams of the outcomes observed at a frequency of 60 Hz and for density differences of 0.25–1.5 g/cm^3 are shown in Fig. 2 for $\phi = 0.58$, and in Fig. 3 for $\phi = 0.60$ and 0.61. In general, features such as those shown in Fig. 1 emerged only at larger values for the density difference, and were absent with zero or negative values of $\Delta\rho$ (particles less dense than the fluid). For the smaller, 50 μm particles, regular patterns of surface waves comparable to Faraday waves were present at lower accelerations; increasing the acceleration yielded the crowns and craters shown in Fig. 1 for $\phi > 0.57$ and sufficiently large $\Delta\rho$ (Figs. 2a and 3a). Under conditions where craters and/or crowns formed, effects of $\Delta\rho$ and ϕ on the threshold values of the dimensionless acceleration Γ were quite complex (Figs. 2a and 3a).

For the suspensions with the 200 μm particles, the dominant features that form involve the suspension shrinking radially and growing in height, in contrast to the behavior of smaller particles, which was characterized by spreading and the formation of craters. For $\Delta\rho > 1$ g/cm^3, above a threshold acceleration the sample shrank radially to form mounds. If the acceleration was increased further, volcanoes or spheres such as those in Fig. 1(c and d) formed. Volcanoes and spheres were observed only at volume fractions above 0.58 and 0.60, respectively. Threshold accelerations tended to decrease with increased $\Delta\rho$. As shown in Fig. 2b, at $\phi = 0.60$ an intermediate state is present where volcanoes such as in Fig. 1c are formed. A video showing the sphere formation process for $d = 200$μm, $\phi = 0.61$, $\Gamma = 14$, $f = 60$ Hz is available as Supplementary Content. A bit of blue dye was added to improve the contrast in the video.

Addition of sodium polytungstate to adjust the density caused the aqueous phase surface tensions to decrease from 72 mN/m for $\rho = 1$ g/cm^3 to 39 mN/m for $\rho = 2.5$ g/cm^3. In order to eliminate possible surface tension effects, the 50 and 200 μm experiments were repeated using aqueous phases that were adjusted to a common surface tension of 38 mN/m by addition of $C_{12}E_{10}$. The results were statistically indistinguishable from the non-adjusted experiments, indicating that surface tension effects were negligible in these experiments. Because the adjusted and non-adjusted results were indistinguishable, the results obtained with surface tension adjustments were included in the results reported here.