LETTERS

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Experimental investigations on the nature of the first wavy instability in liquid-fluidized beds

Maxime Nicolas
Laboratoire de Physique et Mécanique des Milieux Hétérogènes, URA 857 au CNRS, ESPCI, 10 rue Vauquelin, 75231 Paris Cedex 05, France

Jean-Marc Chomaz
LadHyX, URA 317 au CNRS, École Polytechnique, 91128 Palaiseau Cedex, France

Denis Vallet and Élisabeth Guazzelli
Laboratoire de Physique et Mécanique des Milieux Hétérogènes, URA 857 au CNRS, ESPCI, 10 rue Vauquelin, 75231 Paris Cedex 05, France

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Experiments are described which suggest that the first wavy instability of fluidized beds is convective in nature. In particular, this instability is shown to be sensitive to a harmonic forcing localized at the bottom of the bed. © *1996 American Institute of Physics.* [S1070-6631(96)02108-3]

When beds of particles are fluidized, they usually suffer voidage instabilities. In gas-fluidized beds, instabilities manifest themselves as bubbles, i.e, regions essentially devoid of particles which rise through the bed.[1–3] Liquid-fluidized beds are less unstable and exhibit voidage instability waves.[4–7] This first instability remains one-dimensional only in narrow beds. The measured disturbances were shown to grow exponentially upwards along the bed height and eventually to lead to a saturated finite amplitude.[4,5] In wider beds, there is a secondary gravitational overturning instability. A recent conjecture is that bubbles originate from the later development of this secondary instability.[8,9]

Although there is not a general consensus regarding the governing equations of fluidized bed (see, for instance, the reviews of Homsy[2] and Jackson[10] and the work of Batchelor[11]), the different approaches give similar linearized equations for small perturbations of the particle volume fraction in a one-dimensional unbounded bed.[7,12] Most of the linear stability analyses have only considered temporally growing disturbances.[2,10,11] More recently, the stability of an infinite fluidized bed has been investigated with respect to spatially growing disturbance.[12] This spatial stability analysis, which uses the mathematical framework of the open flow theory,[13] reveals the existence of two classes of unstable flows, i.e., convectively and absolutely unstable flows. As the flow rate is increased, the fluidized bed first becomes convectively unstable and then perhaps absolutely unstable. In the convective regime, the fluidized bed behaves as a spatial noise amplifier of the incoming perturbation. In the absolute regime, the instability has an intrinsic behavior and the perturbation grows both temporally and spatially.

The present experimental work focuses on the first wavy instability of liquid-fluidized beds. Its objective is to examine the nature of the unstable flow. In particular, the response of the instability to a localized harmonic forcing is analyzed.

The fluidized bed apparatus was derived from that of Ham *et al.*[7] The fluidized bed consisted of a 2 m vertical cylindrical glass tube with an inner diameter of 6.97 ± 0.02 mm. Particles were glass spheres with a density $\rho_s=4.0\pm0.1$ g/cm^3 supplied by Cataphote and carefully sieved within two adjacent mesh sizes. From the measurements of the projected particle surfaces, the particle diameter distribution was found to be approximately Gaussian with a mean diameter of 685 μm and a standard deviation of 28 μm. It should be mentioned that the bed to particle diameter ratio is small ($\sim$10, i.e., in the lowest limit of the ratio range used in previous experiments[4,5,7]) in order to allow the growth only one-dimensional waves. The fluid was pure water, circulated into the bed by a piston metering pump. The laboratory room was air-conditioned at 23 ± 1 °C. At this temperature, the fluid viscosity was $\eta_f=0.0093\pm0.0002$ P and the fluid density was $\rho_f=0.998\pm0.002$ g/cm^3. The suspension was held by a porous piston which could be either kept immobile or moved with a sinusoidal motion at a given frequency. This piston-type distributor proved to be very useful to study the response of the suspension to a local harmonic forcing. In addition to the porous piston, the uniform distribution of the flow was ensured by a section of tube filled with glass beads with diameter 240 ± 60 μm located before the piston.

With the large particle size studied here, the wave instability was easily observed when the tube was uniformly lit from behind. The waves were recorded with a CCD camera connected to a real time digital imaging system. Spatio-

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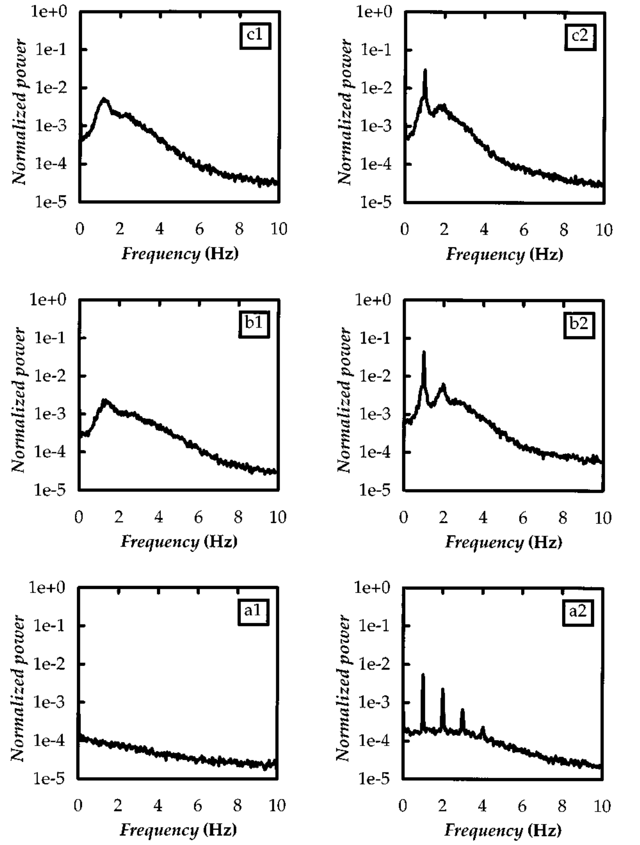

FIG. 1. Power spectra at 5 cm (a), 30 cm (b), 55 cm (c) from the distributor: Without (1) and with (2) forcing ($f=1$ Hz). The mean particle volume fraction is 0.500 ± 0.001, the superficial velocity is 1.7 ± 0.1 cm/s, the Reynolds number (based upon particle diameter) is 12 ± 1 and the minimum fluidization velocity is 0.7 ± 0.1 cm/s.

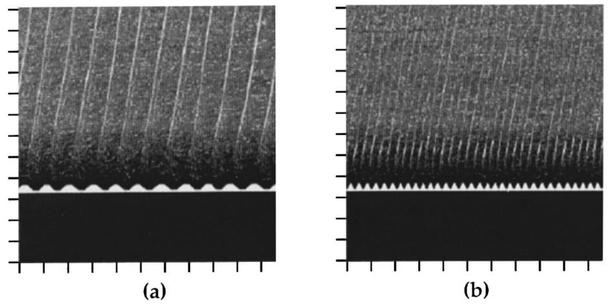

FIG. 2. Spatio-temporal plots: Waves forced at 0.5 Hz (a) and 1.5 Hz (b). The fluidized bed expansion is the same as in Fig. 1. The vertical scale (space) is 1 cm and the horizontal scale (time) is 2 s. In these plots, the inclined white lines correspond to low concentration regions of the suspension moving upward with a nearly constant (phase) velocity of 3.5 ± 0.3 cm/s. The sinusoidal motion of the porous piston can also be seen.

temporal plots of the instability, which are also termed characteristic diagrams,[14] were then constructed. A plot corresponded to the recording of a vertical line of 256 pixels ($\sim$12 cm) versus time. The line was chosen to be located in the middle region of the bed image. Another technique for detecting the wave instability was to use the attenuation of light through the suspension.[4–7] The light source was a stabilized 25 mW He–Ne laser. A linearly responding photodiode was used to detect the transmitted light. The photodiode was mounted on an optical rail which could slide along the height of the tube. The motion of the optical rail was controlled through a personal computer by a stepper motor. After extracting the ac component from the signal with an active filter, power spectra of the fluctuations of the local particle concentration were computed with a dynamic signal analyzer.

As observed in previous experimental work,[4–7] the power spectra were found to be very broad when there was no forcing (or for the ''natural instability''). There was clear evidence, however, of a dominant low frequency $\sim$1.5 Hz. The instability amplitude, which was very small near the distributor, increased along the bed height and eventually saturated as shown in Fig. 1(1).

The sensitivity of the unstable flow to an external harmonic forcing introduced at the bottom of the suspension by the moving piston is presented in Fig. 1(2) and Fig. 2. When a sinusoidal perturbation with a 3 bead diameter amplitude (larger than the ''natural noise'') was applied, the waves were found to be periodic and to follow the forcing (see Fig. 2). A sharp narrow peak corresponding to the frequency of the forcing can be clearly seen in Fig. 1(a2). The smaller peaks correspond to harmonics. Sufficiently far from the distributor, the forced wave amplitudes became larger and eventually saturated [see Figs. 1(b2) and 1(c2)]. The periodic signal due to the forcing and the natural noise spectrum, which are at that distance fully grown, seem to be essentially additive in these regions. This behavior is similar to that observed in the primary convective instability of film flows.[15]

In this work, the nature of the first wavy instability of liquid fluidized beds has been investigated experimentally. The initial wave instability was shown to follow a harmonic localized forcing whereas the ''natural,'' i.e., unforced, instability presented a broad power spectrum. When the forcing (or the ''noise'') was small, the instability amplitude, which was very small at the bottom of the suspension, was also found to increase along the bed height. These experimental findings suggest that the behavior of the bed is dictated by an external forcing (or noise) and therefore that the instability is convective in nature.

With increasing distance from the distributor, nonlinearity dominates the wave evolution, and can lead to amplitude saturation. Even with forcing, the always present natural noise, which also grows along the height of the bed, participates in the nonlinear behavior. The nonlinear evolution of the instability, which is outside the scope of the linear stability analysis of Nicolas *et al.*,[12] needs further experimental and theoretical study. In future quantitative measurements, the influence of particle loadings and wall effects (bed diameter) need also to be examined.

At the present time, no experimental evidence of a transition toward an absolute instability (with a self-sustained resonance) has been observed. It should, however, be mentioned that nonlinear effects or secondary instabilities may hinder the growth of the absolute instability.

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