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Dynamic response of a vibrated fluidized bed of fine and cohesive powders

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ABSTRACT

The dynamics of a fully fluidized bed of group A and group C powders subject to vertical vibration was studied in an 85 mm ID transparent perspex column. Acceleration level was set to $a/g = 1$ and 2 respectively for the two powders. Frequency was varied in the range between 5 and 60 Hz. Different bed mass values corresponding to different bed heights were tested. Time series of the position of the oscillating column wall and those of the oscillating bed height were obtained by means of particle image velocimetry applied to sequences of digitized images of the bed taken by means of a high speed video camera. These time series were used to study the dynamics of the bed surface as a function of the imparted oscillation. A simple model based on a pseudo homogenous approach, assuming the bed as a linear elastic continuum subject to viscous damping, was developed to calculate theoretical values of amplitude ratio and phase lag. Bode diagrams obtained by plotting the experimental values of the amplitude ratio and phase lag were used to fit the two model parameters: the elastic wave velocity and the viscous dissipation coefficient. Comparison between model and experiments is fairly good in terms of phase lag. The model amplitude ratio, instead, fails to exactly describe the experiments close to the natural resonance frequencies of the system at which larger ratios are expected and generally found. In particular, for the group A powder the oscillation of the particulate phase is more complicated than predicted due to the appearance of multiple concentration fronts close to the bed surface. The fitted elastic wave velocity is in close agreement with the equation proposed by Roy et al. (Chem. Eng. Sci, 45, 1990, 3233–3245). A new proposed model for the viscous damping coefficient based on wall friction interaction between the bed of powders and the column is able to predict satisfactorily the experimental data.

1. Introduction

In industrial applications of powder technology, vibrations have been used together with fluidization in order to overcome cohesion problems arising in the treatment of sticky particles, as for example in the case of powder drying operations [1] or of very cohesive powders [2]. Vibrations, in fact, are able to interact directly with structures of the dispersed phase determined by cohesive forces such as aggregates and channels. Vibrations can be applied with the use of mechanical oscillations [3] or with the use of sound waves [4] or combining both [5]. In particular, application of sound has been proved to be very effective for the fluidization of fine powders belonging to the group C of the Geldart [6] classification [7–10]. Russo et al. [8] demonstrated that this kind of vibration technique was able to break particle aggregates when acting at the resonance frequencies of the aggregate structure (>100 Hz). Also mechanical vibration was demonstrated to be effective on group C powders [11–26] by breaking the aggregates into smaller pieces which become primary fluidizable particles. These smaller aggregates may fluidize homogeneously as typical Group A powders. The effectiveness of mechanical vibrations has also been proven, even at frequencies lower than those in the range in which acoustic vibrations are effective. This finding supports the idea of different mechanisms of action of acoustic waves and mechanical vibrations on fluidized beds. It is clear that the full understanding of the fluidization promotion of fine powders can only come from a complete assessment of the effects of vibration on Group A powders [13,14,27–31]. In particular, in spite of the fact that often vibration frequency is considered a fixed parameter of the vibro-fluidization procedure, in several experiments it appears that vibration frequency is a key parameter in the determination of the mechanics of the fluidized bed and in the effectiveness of the imparted vibrations [18,20,21,24–26].

Several models have been developed to describe the effect of the application of vibrations on the mechanics of powder beds. Some models are available for fluidization of beds of powder due to the effect of vibrations both using a concentrated parameter approach [32,33], also evaluating dissipation [34], and using a distributed parameter approach [35], accounting also for specific boundary conditions [36]. In gas fluidized beds subject to vibrations the system compressibility is highly affected by the fluidizing gas as demonstrated by Roy et al. [37] who were able to describe the vibration dynamics of a fluidized bed by means of a pseudo homogeneous model. Also for gas fluidized beds, both concentrated parameter models, as that proposed by Wang et al. [29], and two phase distributed parameter models, as that proposed by Weir [38], are available.

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In this paper the dynamics of a fluidized bed of a group A powder and of a group C powder subject to vertical vibration is studied by measuring the bed surface motion at different vibration frequencies between 5 and 60 Hz and comparing the powder bed response to the imparted oscillation in terms of amplitude ratio and phase lag. A simple distributed parameter and pseudo homogenous model is used to describe the system dynamics.

2. Theory

In agreement with the Roy et al. [37] approach, the vibrated fluidized bed will be described as a pseudo continuous one-dimensional system. The equation referred is that used to describe the propagation of vibration on an elastic rod (Fig. 1) with viscous damping:

$$\frac{\partial^2 x}{\partial t^2}+\gamma\frac{\partial x}{\partial t}-c^2\frac{\partial^2 x}{\partial y^2}=0 \qquad (1)$$

where x is the local displacement produced by vibration, y and t are the space and time coordinates, c is the vibration propagation velocity and γ is the viscous damping constant. In our case the system is subject to a forced oscillation at its bottom ($y=0$) while it is free at the top ($y=H$), i.e. there cannot be elastic compression. This situation is described by the following boundary conditions:

$$x\Big|_{y=0}=A(0)\sin(2\pi f t) \quad \frac{\partial x}{\partial y}\Big|_{y=H}=0 \qquad (2)$$

where $A(0)$ and f are the amplitude and the frequency of the imparted oscillation. In our system we are not interested in the initial transient depending on the initial condition, and therefore, we look at the stationary solution at long time for which no initial condition is needed. We will report here the stationary solution x_1 at the bed surface ($y=H$) for the underdamped case, that is apparently the case for the fluidized bed when a periodic response is observed and applies if $2\gamma H/\pi c<1$:

$$x_1\Big|_{y=H}=\frac{A(0)\sqrt{2}}{\sqrt{\cos(2\beta H)+\cosh(2\delta H)}}\sin(2\pi f t+\phi) \qquad (3)$$

where

$$\delta=2\pi\sqrt{\frac{-f^2+\sqrt{f^4+(\gamma f/2\pi)^2}}{2c^2}},\ \beta=2\pi\sqrt{\frac{f^2+\sqrt{f^4+(\gamma f/2\pi)^2}}{2c^2}} \qquad (4)$$

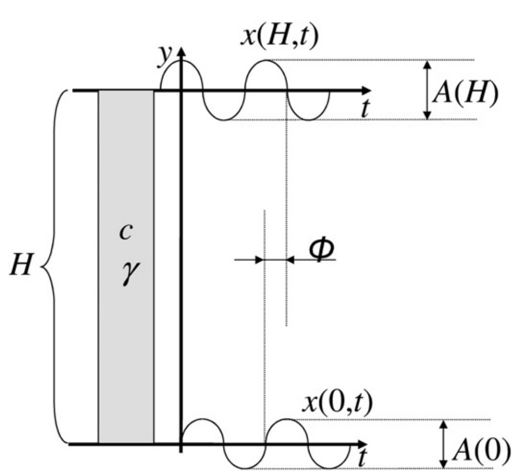

Fig. 1. Schematic representation of the model adopted to describe vibration propagation within the vibrated bed.

and the phase lag, ϕ, between vibration amplitude measured at surface and that imparted to the bed is such that:

$$\cos\phi=\frac{\sqrt{2}\cos(\beta H)\cosh(\delta H)}{\sqrt{\cos(2\beta H)+\cosh(2\delta H)}} \quad \text{and} \qquad (5)$$
$$\sin\phi=-\frac{\sqrt{2}\sin(\beta H)\sinh(\delta H)}{\sqrt{\cos(2\beta H)+\cosh(2\delta H)}}.$$

This solution can be used to evaluate the amplitude ratio, AR, between the vibration amplitude measured at surface and that imparted to the bed:

$$AR=A(H)/A(0)=\sqrt{2}/\sqrt{\cos(2\beta H)+\cosh(2\delta H)} \qquad (6)$$

and the phase lag:

$$\phi=-|\pi(1+\sin\phi/|\sin\phi|)-\arccos(\cos\phi)|. \qquad (7)$$

In the considered underdamped case the model yields natural resonance frequencies at:

$$f_n=(2n+1)c/4H \text{ with } n=0,1,2,3\ldots \qquad (8)$$

At resonance frequencies the amplitude ratio shows a local maximum and the phase lag assumes values of $-\pi/2-n\pi$.

3. Experimental

3.1. Apparatus

The core of the apparatus is a fluidization perspex column 85 mm ID and about 400 mm high (Fig. 2). The air is distributed at the column base by a 10 mm thick porous plate of sintered brass particle of about 10 μm diameter. The porous plate is clamped in the flange connecting the air wind box and the fluidization column. In the column flange a pressure port is connected to a U-tube manometer filled with water. Desiccated air from the laboratory line is fed to the wind box by a thermal mass flow controller (Fe-7700 Aera, F) with a maximum flow rate of 0.17×10^{-3} std m^3 s^{-1} (0 °C and atmospheric pressure).

The column is fixed to the vibrating plane of the actuator by means of a rigid steel and aluminum structure. The actuator is an electric inductance vibrator (V100 Gearing and Watson, USA) which is able to produce a sinusoidal vertical movement in the range 2–6500 Hz with displacement amplitudes up to 12.7 mm, exerting a maximum force of 26.7 kN. The vibrator amplifier is connected to a vibration controller Sc-121 (Labworks Inc., USA) which is able to work with frequencies between 2 and 6500 Hz. The controller measures the effective vibrations by means of a piezoelectric accelerometer (8636B60M05 Kistler, USA) fixed on the metal structure supporting the fluidization column.

The bed surface motion was recorded by a Kodak Ektapro HS4540 motion analyzer digital high speed video camera. This apparatus provides with sequences of digitized images with a resolution of 256×256 pixels in a 256 gray level scale. A recording rate of 4500 frames/s was set to properly follow the dynamics of the oscillations. The video camera was coupled with a 75 mm lens; extension tubes between 20 and 60 mm were used for macro purposes as a function of the amplitude of the observed bed surface oscillation. The corresponding field size was between 13.9 and 1.6 cm^2.

3.2. Materials

Two powders were used in the experiments, an aeratable powder and a cohesive powder, namely a fluid cracking catalyst (FCC) powder and a potato starch powder. Powder properties are summarized in Table 1. Particle size distributions were measured with a Malvern