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Experimental and numerical study of solids circulation in gas-vibro fluidized beds

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ABSTRACT

The effects of vertical, sinusoidal vibrations on the fluidization behavior of a granular bed are studied, where we focus on the solid circulation rate and its dependence on the vibration parameters. To this end, an experimental study was performed in a pseudo-2D bed, and the optical non-invasive measurement technique particle image velocimetry was employed to obtain whole field velocity information. Additionally, discrete element model (DEM) simulations were performed and the time-averaged fields were compared. In both simulations and experiments, it was found that the solid circulation rate at constant vibration frequency increases with acceleration, in agreement with other experimental findings reported in literature. Gas-vibro fluidization generally exhibits larger circulation rates as compared to conventional gas-fluidization.

1. Introduction

In a well-operated fluidized bed reactor, there is an intensive contact between the solid phase and the gas phase, so that heat and mass transfer rates can be maximized. Very fine particles, that is, A and C powders in the Geldart classification, have a high surface area per unit volume of the reactor, which makes them very attractive for processes involving gas–solid and solid–solid reactions. However, when the size of the particles in the powders becomes less than, say, 10 μm (C powders), the effect of the attractive forces between particles becomes relatively large and agglomerates can be formed. These agglomerates can cause the formation of stable channels and the fluidization behavior becomes poor since the gas will preferably flow through the channels. Similar problems can occur when sticky particles are employed. Fortunately, there are methods to overcome or avoid the formation of stable channels, for instance by applying (vertical) vibration to the fluidized bed (gas-vibro fluidization), or by the use of pulsed gas-fluidization. The transfer of vibration or pulsation energy into the granular assembly can diminish or even completely suppress channeling. In this work we focus on gas-vibro fluidization.

Gas-vibro fluidization knows many (potential) applications which are all related to enhancing the fluidization quality of difficult-to-fluidize particles. Typical examples are the drying of organic fine particles, or the removal of organic solvents from particles [1]. Also enhanced mixing of particles with different properties can be achieved, a typical example of which is the mixing of differently sized nano-particles for the preparation of nano-composites [2], but also granulation of small particles or the nitriding of steel [3]. The surface-coating (for example chemical vapor deposition) of small particles is also a potential application, in particular for gas-fluidization under low pressures [4,12]. Also, some chemical reactions have been carried out under gas-vibro conditions, such as methane oxidative coupling [5]. The reason for this is that most of the catalysts for this process contain alkaline or alkaline earth compounds, which were often found to melt under operating conditions, leading to agglomeration of the catalyst and potential de-fluidization. So, maintaining a properly fluidized bed is important in order to avoid the formation of hot spots. One of the most important industrial applications of gas-vibro fluidized beds is where they are employed as dryers of the plug flow type, where horizontal transport is imposed by a forward directed gas flow [6]. This equipment operates with a limited height of bed material (say 60 cm), and for this reason most research papers on this topic consider only shallow powder layers (usually smaller than 20 cm).

In this paper, we will employ both experiments and numerical simulations to investigate the effect of the vibration on the solid circulation rate in gas-vibro fluidized beds. This quantity is an important index for heat transfer via the particle phase, and is strongly influenced by the bubble behavior. Additionally, the experiments can give an indication as to how far the numerical model is able to predict the gas-vibro fluidization behavior. The paper is organized as follows: we will first give a short overview of experimental and simulation work in literature, where we will mainly focus on gas-vibro fluidization. Next, we will describe the experimental set-up and briefly discuss the used measurement technique (PIV). Following this, we will discuss the simulation method, and more specifically the simulation parameters that we used. Finally, we will discuss the experimental observations and compare these with the model predictions, where we focus upon the solid circulation rates

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of a conventional gas-fluidized bed, and observe how these are affected by the different modes of vibration.

2. Short literature overview

In literature, fluidized beds are most commonly vibrated in the vertical direction, but also vibrations in the horizontal plane and twist vibrations have been studied [1,7–15]. A comprehensive overview with respect to the subjects of different papers is provided in Table 1, the main findings of which we briefly summarize below.

For the purpose of coating very fine particles it has been suggested that gas-vibro fluidization under low pressures can be of interest [8,4,13]. According to Wank et al. [4], atomic layer deposition – used for obtaining ultra-thin films – may require reduced pressure, and vibrations can assist in obtaining the fluidized state. Also, the drying of thermo-labile substances such as foods and pharmaceuticals can be done under reduced pressure, which allows for operating the fluidized bed at lower temperatures [13]. For Geldart A powders it has been found that gas-vibro fluidization can increase the gas velocity window of homogeneous fluidization [21,11], which is attributes to the break-up of bubbles into the emulsion phase. Jin et al. [20] found that vibrations may even increase homogeneity for Geldart B and D powders. Zhou et al. [7] have investigated the bubble motion pattern and rise velocity in horizontally and vertically vibrated beds. For vertical vibrations, they found that the bubble rise velocities are larger compared to those in the absence of vibration, although for frequencies above a certain threshold, no further increase of the rise velocity was observed. Mawatari et al. [23] investigated 60 μm glass beads under vertical vibration and performed experiments at a fixed frequency of 40 Hz, so that the vibration strength could only be modified via the vibration amplitude. They observed that when the vibration strength Γ was increased beyond a certain threshold value, the descending particle flow was enhanced, so that the area available for rising bubbles was reduced and coalescence of bubbles was promoted. Vibrations need not to be limited to vertical vibration only, and horizontal vibrations or a combination of horizontal and vertical vibrations may also be used. Some researchers found a negative effect on the fluidization quality when only horizontal vibrations are applied in a gas-vibro fluidized bed, resulting in cracks between the side walls and the granular bed and gas bypassing [1,18], while others found that the application of horizontal components (which may be in combination with vertical vibration) was more effective for breaking channels in cohesive powders [10,1].

Note that there is currently some controversy about how the vibration energy is precisely transferred in gas-vibro fluidized beds. Some authors observe that the kinetic energy, gained by particles when colliding with the bottom plate, is lost in the lower sections of the granular bed due to the inelasticity of particle collisions, so that the vibrations have no significant effect on the behavior of particles located higher in the bed [16–20]. Others argue that the vibrations induce pressure and gas velocity fluctuations and that this is the dominant energy transfer mechanism, where even particles that are far removed from the bottom plate may be affected [4,21,22].

The aim of the current study is to investigate to what extent the vibrations could affect the solids circulation, which is closely linked to the bubble behavior. To this end, we kept the aeration rate at a fixed value of 1.5 times the minimum fluidization velocity, and varied the vibration amplitude and frequency. Note that another interesting effect of vibrations is that it can lower the fluidization velocity, however, this was not the subject of the present study.

Table 1
Overview of the literature discussed in this paper. The references marked with an asterisk are simulation studies.

Vertical vibration	Horizontal vibration	Twist vibration
[16,17,1,3,5,4,10,21] [18*,7,20,2] [19*,23,22*]	[1,10,7]	[1,8–10] [11–15]

3. Experimental set-up and procedures

We performed gas-vibro fluidization experiments in a pseudo-2D gas-fluidized bed, which has dimensions of 15 × 1.5 × 60 cm^3 (see Fig. 1 for a schematic overview). The front and back wall are glass plates, while for the side walls aluminum strips are used. In order to achieve an even gas distribution at the base of the set-up, we employ a sintered steel plate of thickness 2 mm with an average pore size of approximately 10 μm. The entire construction was mounted on a shaker (Tira TV 50301), which can deliver a well-defined, sinusoidal driving, with a force up to 2700 N. An accelerometer (Endevco Isotron 751-100) measures the vibration characteristics and a control system ensures that the desired operating conditions are obtained. A high speed digital camera (LaVision Imager Pro) is positioned in front of the bed to record the images for PIV analysis, where two halogen lamps are used to illuminate the set-up. Air was used as fluidization gas, which was humidified by adding steam in order to reduce the effects of static electricity. Due to this humidification procedure, it was not possible to keep the gas temperature fixed at exactly the ambient temperature (293 K): during the day temperatures could increase to 303 K, leading to an increase in the superficial gas velocity of approximately 3%. However, it is expected that the effect on the observations is small, especially compared to the effects caused by the vertical vibrations.

We performed experiments with glass beads with a narrow size distribution, where the average diameter was 1.015 ± 0.02 mm and the height of the settled granular bed was 15 cm. We determined the minimum fluidization velocity (u_{mf}) of these particles by pressure difference hysteresis and found it to be 0.65 m/s. In the experiments, we used a superficial gas velocity of 1.5 × u_{mf} (i.e., 0.98 m/s). The measurement procedure was as follows. Once the system was set into vibration at the desired shaking parameters, we let the fluidized bed initialize at working conditions for 2 min, after which the measurements were performed. These measurements consist of recording image pairs with the high speed digital camera, which allows for the measurement of the instantaneous velocity fields (more details follow below). For the camera settings that we used, the maximum duration of the measurements was 2 min. The vibration can be characterized by 2 parameters, namely frequency f_z and amplitude A_z. The maximum acceleration (normalized by gravity) is then:

$$\Gamma = \frac{(2\pi f_z)^2 \cdot A_z}{g}. \tag{1}$$

We investigated 4 different values for the acceleration (Γ), where the vibration parameters are displayed in Table 2. There were certain limitations for the vibration parameters, since the maximum amplitude of the shaker was 10 mm. Additionally, from preliminary experiments it had become clear that small variations in the vibration frequency could lead to different bubble behavior. Therefore, we chose to increase the vibration frequency only in small steps of 2.5 Hz. In Fig. 2 we show, as an example, some snapshots of the vibro-fluidized bed, shaken with a frequency of 7.5 Hz, and an amplitude of 8.84 mm.

The measurement technique employed in this work is particle image velocimetry (PIV). PIV, originally developed in the field of experimental fluid dynamics, is a non-intrusive optical measurement technique which can be used to obtain the instantaneous fluid velocity field of a continuous fluid [24,25]. To visualize the flow in transparent fluidic systems, small tracer particles are dispersed. As the fluid is illuminated by a laser sheet, the tracer particles reflect light and an image

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