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Sound waves in fluidized bed using CFD–DEM simulations

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ABSTRACT

The speed of sound waves in a fluidized bed is investigated using CFD–DEM numerical simulations. Appropriate initial and boundary conditions are applied to reproduce bed phenomena. The effect of varying the height of the bed is also studied. The results of the simulations matched those from the literature. The pressure and particle velocity profiles obtained feature oscillatory behavior to which functions (based on a damped standing wave) were fitted, enabling an explicit dependence on time and space variables to be established. These fitted functions were substituted into the linearized governing equations for the two-phase flow. These solutions enabled a new relationship to be derived for the speed of sound and damping in the system. The conclusion drawn is that the damping in the system is governed by the effective bulk viscosity of the solid phase, which arises from the particle viscosity.

Introduction

The presence of particles in a gas phase (as in a fluidized bed) is known to affect the propagation of sound waves through the continuous phase. Cahan (1990) retrospected an earlier study of sound waves conducted in the 1860s and 1870s whereby lycopodium seeds were sprinkled into an oscillating column of air within a tube to identify the nodes of a standing wave. In the presence of particles, sound waves attenuate and the speed of sound that is measured differs from its theoretical value in air. Later, Mallock (1910) described a study of the velocity of sound in liquid–gas mixtures such as froths. The results also showed that the speed of sound differed from the value in gas in a similar manner to that concluded in Cahan (1990). Roy, Davidson, and Tuponogov (1990) reports on the same topic for a gas fluidized bed. They cross-correlated the pressure signal at different heights of the bed to detect the speed of the moving disturbance and measured the frequency of the standing wave after a disturbance had been introduced to infer wave speed. Again the speed of sound was significantly lower in the gas–particle medium.

Lamb (1963) gives the expression for the velocity of a sound wave u_s in a continuous compressible medium as:

$$u_s = \sqrt{\frac{dp}{d\rho}}, \tag{1}$$

where $dp/d\rho$ is the rate of change of pressure with bulk density. To apply this expression to a two-phase mixture of gas and particles, a number of assumptions need to be made (Roy et al., 1990), which were later acknowledged in Bi, Grace, and Zhu (1995) and Bi (2007). These assumptions are also adopted in Mallock (1910), Tangren, Dodge, and Seifert (1949), and Campbell and Pitcher (1958):

1. The particles and gas move together (i.e., homogenous rather than separated flow),
2. The gas is compressible and obeys the ideal gas law,
3. The particles are incompressible,
4. The particulate matter and gas are isothermal.

The assumption that the gas and particles are in an isothermal state can be justified by computing the time required for solid and gas to attain the same temperature (Roy et al., 1990). This assumption might not be valid in fluidized beds with larger particles because increasing the size of particles increases the time constant value, hence, increasing the time taken by the system to reach thermal equilibrium. A similar conclusion is reached in Turton, Fitzgerald, and Levenspiel (1989) and Kunii and Levenspiel (1991).

Roy et al. (1990) gives a derivation of an expression for the speed of sound in a homogenous two-phase medium,

$$u_s = \sqrt{\frac{\rho_g R T_g}{\varepsilon\left(\rho_s(1-\varepsilon)+\rho_g\varepsilon\right)}}, \tag{2}$$

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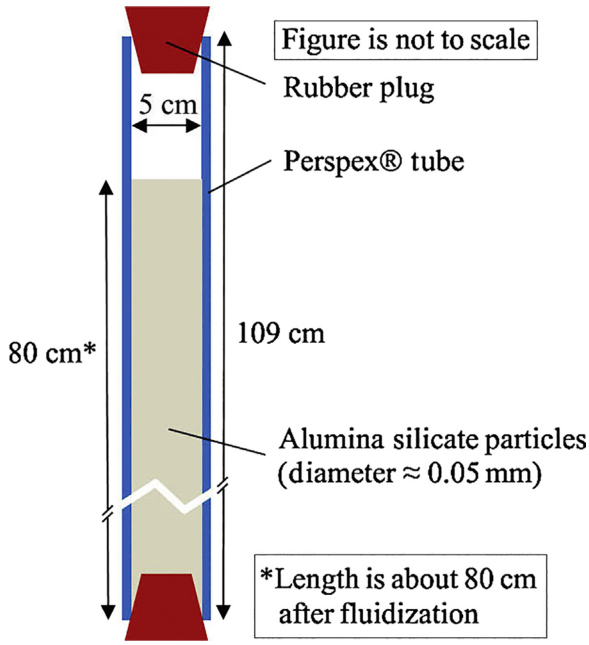

Fig. 1. Experiment setup to study the standing wave in a fluidized bed.

where ρ_s and ρ_g are the respective densities of solid and gas, ε is the void fraction, T_g the absolute gas temperature, and R the specific gas constant. Note that this expression is only valid when the value of voidage is less than one ($\varepsilon < 1$). Roy et al. (1990) presents an experimental demonstration that the speed of sound in a fluidized mixture of sand and air is typically 1/30 of the speed of sound in air. Similar results were reported in Bi et al. (1995); the speed of sound was shown to be 10 m/s in a fluidized mixture of air and fine particles (50 μm in diameter with a density of 1580 kg/m^3).

Roy et al. (1990) also suggested a theoretical relation for the damping time τ relationship, derived by assuming a system comprising a mass attached to a spring with viscous damping,

$$\tau = \frac{2g}{\omega^2 U_{mf}}, \quad (3)$$

where g is the gravity constant, ω the angular frequency of the oscillation, and U_{mf} the minimum fluidization velocity.

In this work, the speed of sound in the fluidized medium is verified through experiments and numerical simulations employing computational fluid dynamics (CFD) and discrete element modeling (DEM). The results are also analyzed analytically, revealing the importance of particle viscosity in the damping of sound waves in the fluidized bed.

Experimental verification of speed of sound in a fluidized medium

An experiment was setup to characterize the standing wave created in a fluidized medium. Roy et al. (1990) associated such standing waves with the speed of sound. Their explanation is based on the analogy with an organ pipe, with one end closed and the other open. The simple experiment was setup to observe this behavior (Fig. 1) comprised a Perspex® tube with an internal diameter of 5 cm and an external diameter of 6 cm. The two ends of the tube are sealed with rubber plugs. The tube is filled with alumina silicate particles (diameter ≈50 μm). These particles are fluidized by rotating the tube vertically for a few revolutions. During the rotation, the particles are subjected to a centrifugal force, building a relative velocity between gas and particles. This causes the particles to fluidize, i.e., the powder gas mixture becomes free-flowing, and a horizontal level ‘free surface at meniscus’ forms, regardless of the tilt of the tube. In addition, a significant expansion in the fluidized bed is noted before and after fluidization. Once fluidized, an impact load is induced in the fluidized medium by striking the tube on the ground. This induces vertical oscillations in the fluidized medium, corresponding to a standing wave in the medium. The frequency of these oscillations is noted by making a video of the meniscus of the fluidized medium at 30 Hz using a digital camrecorder (Handycam DCR-HC14E, Sony, Japan). A .wmv clip was captured and converted into image files. Fig. 2 shows several images of the oscillation in the fluidized medium as captured using the above-described experimental setup.

The captured images were analyzed to estimate the wave frequency. The average time period for a single oscillation in the experiments was 0.286 s, which corresponds to a frequency of 3.50 Hz. The length of the wave can be found from the height of the fluidized medium in the tube. The height after fluidization was 80 cm corresponding to a quarter standing wave in a tube with one end closed and the other open. Therefore, the complete wavelength of the standing wave is 320 cm giving a value for the speed of sound of 11.2 m/s.

The results found through experimentation were compared with the speed of sound given using Eq. (2). The values of parameters used are as follows: the density of alumina silicate particles

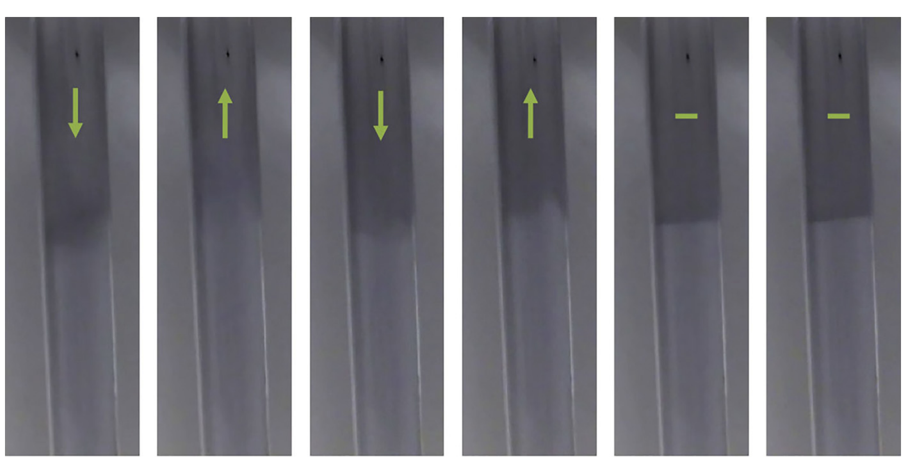

Fig. 2. Variation of top meniscus of the fluidized bed captured at 30 Hz with green arrows indicating the direction of oscillation on the free surface. Elapsed time is shown below each image.

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