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Parameters of surface standing waves in fluidized bed apparat with different diameter

M I Ershov [1,2]*, V G Tuponogov [1], N A Abaimov [1], A F Ryzhkov [1]

[1]Ural Federal University, Ekaterinburg, Russia
[2]Company group «PLM-Ural», Ekaterinburg, Russia
E-mail:ershov1807@gmail.com

Abstract. Regarding medium- and low-temperature processes of heterogeneous heterophase interaction in the units for cleaning from pollutants and trapping CO_2, the analogy of the behavior of standing surface waves of an ideal liquid with oscillations of the surface of a fluidized bed is considered. Waves on the surface of a fluidized bed are formed when gas bubbles leave it and are one of the elements of the mechanism of self-sustained fluctuations of the entire mass of the bed. The frequency modes of the surface waves correspond to the main modes in the spectra of pressure fluctuations in the bed and depend on its geometry. The fluctuations of a bubble three-dimensional fluidized bed in apparatuses of different sizes are numerically simulated in a high-performance parallel computing mode using the Ansys Fluent program. Comparison of analytical calculations for fluid oscillations in a vessel with the results of numerical simulation of a fluidized bed and experimental data on the frequency of the emergence of bubbles and modes of surface waves is carried out.

1. Introduction

Fluidization is used to carry out a variety of physical and chemical processes in which effective contact is required between the gaseous medium and the developed surface of a dispersed solid material.

One of the actual and promising areas of application of apparatus with a bubble fluidized bed (BFB) is the decarbonization of gas combustion products with ash and slag waste from power and energy-intensive industries [1]. The stabilization of ash and slag wastes achieved in the process of carbonization allows them to be used in the construction industry instead of natural ones, to reduce CO_2 emissions [2].

The efficiency of heat and mass transfer processes in BFB is determined by the hydrodynamic parameters of the apparatus, which include the resistance of the gas distributor, the uniformity of fluidization over its area [3] and hydrodynamic interaction between bed and air-plenum chamber [4]. In calculations of the interphase interaction processes in the bed, the size of bubbles and their distribution in the volume of the bed are used, which are determined on the basis of models of self-sustained fluctuations of the bed mass [5–7] and the corresponding them dynamic pressure fields [8, 9]. Experimental studies show that the appearance and propagation of pressure waves in the bed depends on the mechanism of the exit of gas bubbles to the bed surface [10-12]. The discrete nature of the change in the main fluctuation frequency can be explained by the change in the fluctuation modes of the fluidized bed surface [13, 14]. Bubble surface waves in a fluidized bed are one of the dominant hydrodynamic phenomena not only in the bubble fluidization bed, but also in the bottom bed of a circulating fluidized bed [15].

Calculation of unsteady pressure fields in a fluidized bed is an urgent problem in the study of the hydrodynamics of the bed. The Euler model in ANSYS Fluent allows one to simulate the flow of particles with a high packing density including complex mechanisms of interphase interaction.

Despite rigorous mathematical modeling of fluidization, the laws of interfacial friction used in the model are still semi-empirical. Therefore, it is extremely important to use the laws of resistance, which would correctly predict the state of minimum fluidization, in which the bed of particles is in suspension. With the right approach, a balance must be ensured between the mass forces and the forces of the interphase friction. Simulation allows studying the mechanism of bubble formation and unstationary fluidized bed hydrodynamics.

The purpose of the work - validate the proposed fluidized bed model and, with its help, study the parameters of surface standing waves in apparatus with a fluidized bed with different diameters of apparatus. The paper is structured as follows: the method of modeling is stated in Section 2; the results and discussion are presented in Section 3; Section 4 presented the conclusions derived from the results of the study.

2. Model and Method

The calculations were carried out for copper particles with a density of 8560 kg/m^3 with a diameter of 460 μm and a sphericity of 0.85, according to experimental data [16]. The minimum fluidization velocity is 0.395 m/s. Six variants of cylindrical fluidized beds of various diameters (from 0.045 m to 0.265 m) were calculated. For all experiments, the same values of the initial bed height of 0.088 m were set, as well as the air speed of 1 m/s. The calculation time for beds is from 10 to 17 seconds. The calculation results show the area averaged frequency of pressure fluctuations in the input plane ($x = 0$, $H = 0$). The values of the fundamental frequency of pressure fluctuations were obtained by the method of spectral analysis of the calculated time diagram of pressure fluctuations. Continuous phase waves on the bed surface were represented by isosurfaces with a volume fraction of particles of 0.4 (top view).

The simulation used the Gidaspow aerodynamic drag model, corrected for particle sphericity, built into Ansys Fluent 2020 R2 using a UDF. The flow was simulated as a laminar one, on the walls for both phases, the No Slip condition was set. The Gidaspow model [17] is a combination of the Wen and Yu model [18] and the Ergun equation [19]. The model is recommended for dense fluidized beds. When $\alpha_l > 0.8$, the fluid-solid exchange coefficient K_{sl} is of the following form:

$$K_{sl} = \frac{3}{4} C_D \frac{\alpha_s \alpha_l \rho_l |\vec{v_s} - \vec{v_l}|}{d_s} \alpha_l^{-2.65}, \tag{1}$$

where α_s and α_l – the volume fractions of particles (solid) and gas (liquid), respectively; ρ_l – the gas density; v_s and v_l - the terminal velocities of particles and gas, respectively; d_s - the diameter of particles; C_D is the drag coefficient, that is based on the relative Reynolds number (Re_s):

$$C_D = \frac{24}{\alpha_l \mathrm{Re}_s} [1 + 0.15(\alpha_l \mathrm{Re}_s)^{0.687}]. \tag{2}$$

When $\alpha_l \leq 0.8$, K_{sl} takes this form:

$$K_{sl} = 150 \frac{\alpha_s (1 - \alpha_l) \mu_l}{\alpha_l d_s^2} + 1.75 \frac{\rho_l \alpha_s |\vec{v_s} - \vec{v_l}|}{d_s}, \tag{3}$$

where μ_l – the viscosity of gas.

For all geometries, a structured hexahedral mesh was built in the Space Claim Meshing editor with a mesh size from 1 mm to 5 mm, for diameters from 0.045 to 0.265 m, respectively. The size of the cell was selected so that the mesh size did not exceed 200 thousand elements (Fig. 1), while there were at least 30 cells along the diameter, and so that the conditions for the operation of a homogeneous model of aerodynamic resistance were met.

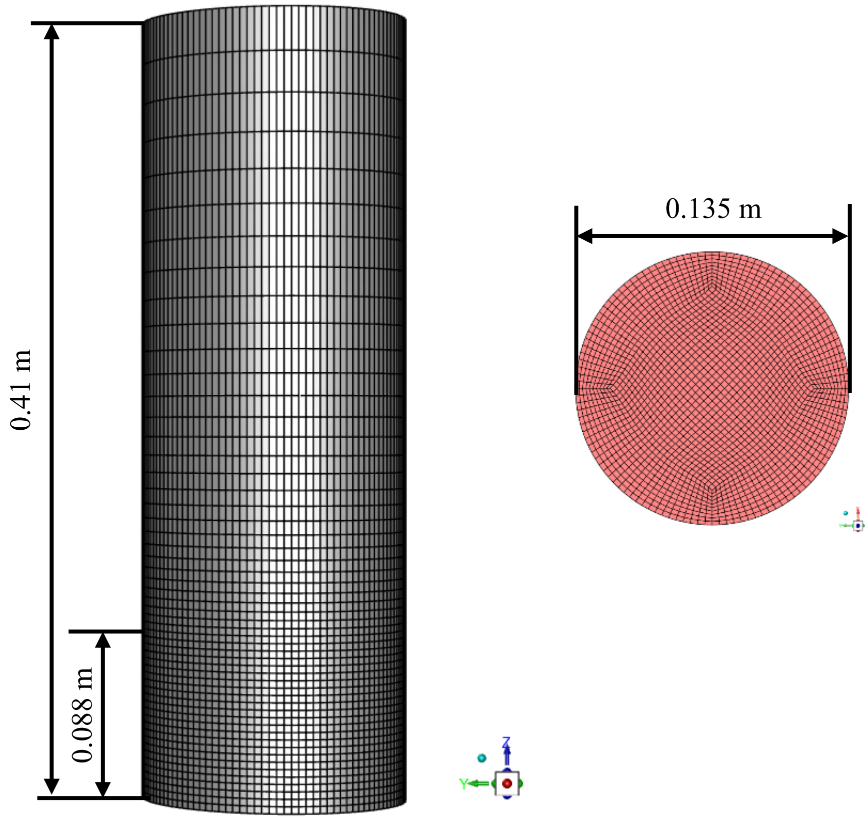


Figure 1. Mesh for case with D = 0.135 m.

The flow velocities and pressure are coupled according to the SIMPLE scheme. The gradient is sampled using the Least Squares Cell Based scheme, the pressure is sampled using the PRESTO scheme, and the momentum, volume fraction and transient term are sampled using the First Order scheme. The time step is 0.001 seconds, the lower relaxation coefficients are taken by default.

In this work, the simulation results are compared both with experimental data and with calculations of the frequency of two interrelated phenomena: pressure fluctuations in the bed caused by the emergence of bubbles from it, according to the Baskakov, etc. formula [10]:

$$f = \frac{1}{\pi}\sqrt{\frac{g}{H}}, \tag{4}$$

where H is the fixed bed height, and standing surface waves on the surface of a liquid in a vessel of this deformation according to the Sun, etc. formula [13]:

$$f = \frac{1}{2\pi}\sqrt{m_{np} g\, tanh(m_{np} H)}, \tag{5}$$

where m_{np} is the wavenumber with the numbers of half-waves n and p.

3. Results and discussion

In fig. 1 shows the dependence of the natural frequency of fluctuations of the bed on the ratio of the diameter to the height of the bed. Points - experimental [16] or Ansys Fluent modeled frequency values on a specific geometry. The dashed line is the natural frequency of fluctuations of the bed according to formula (4) at a height of H = 0.088 m (does not depend on the diameter of the installation). Solid lines - calculation of the natural frequency of fluctuations of the bed by formula (5) from the number of half-wavelengths (n) along the diameter of the installation under the assumption that the behavior of standing surface waves of an ideal fluid is analogous to fluctuations of the surface of a fluidized bed. From the graph it can be concluded that, in contrast to formula (4), the standing wave technique [13, 14], formula (5), shows that the bed frequencies can vary discretely, depending on the number of half-waves along the installation diameter, but within a constant the number of half-waves, the frequency will decrease with an increase in the ratio of diameter to height.

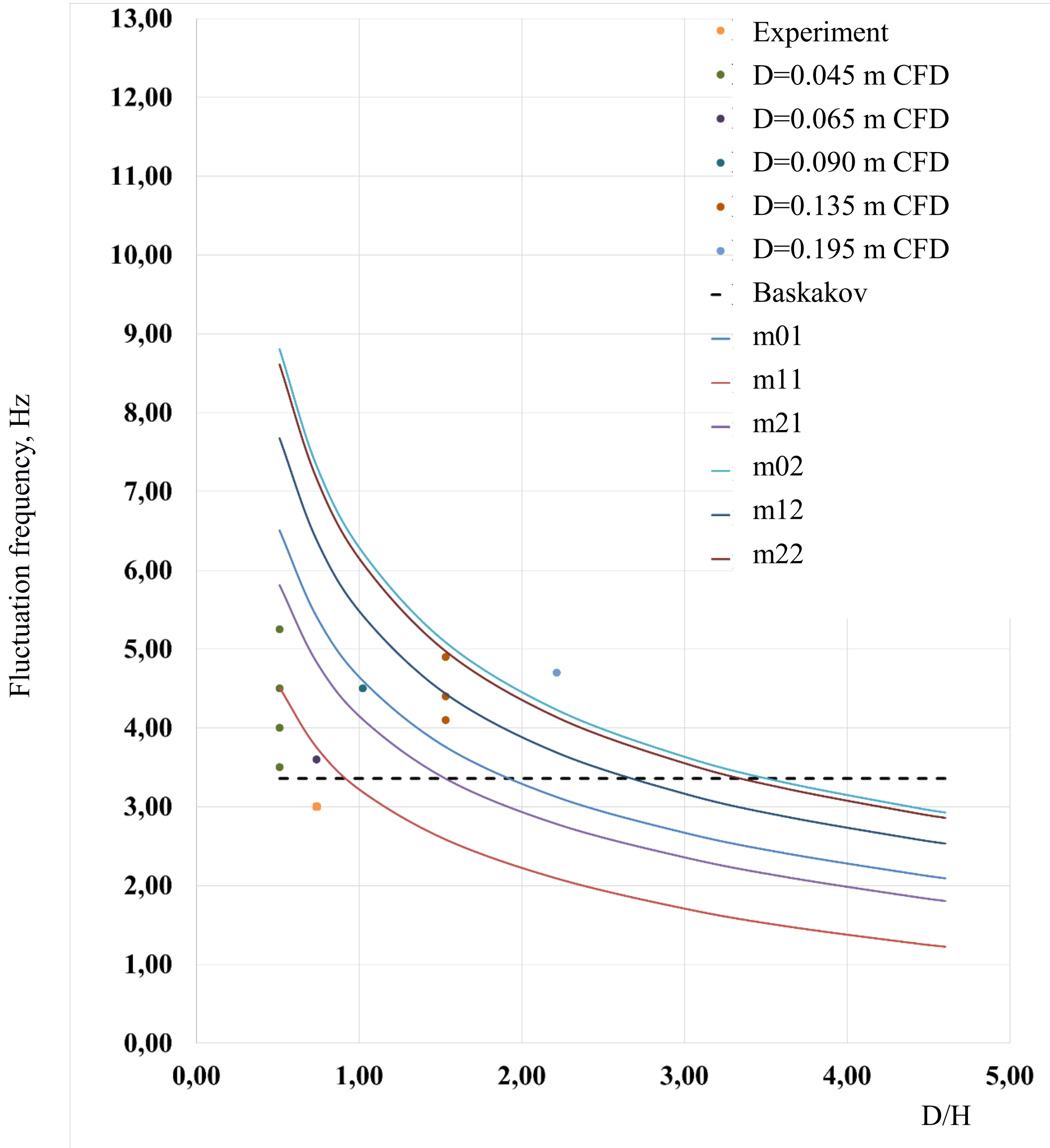
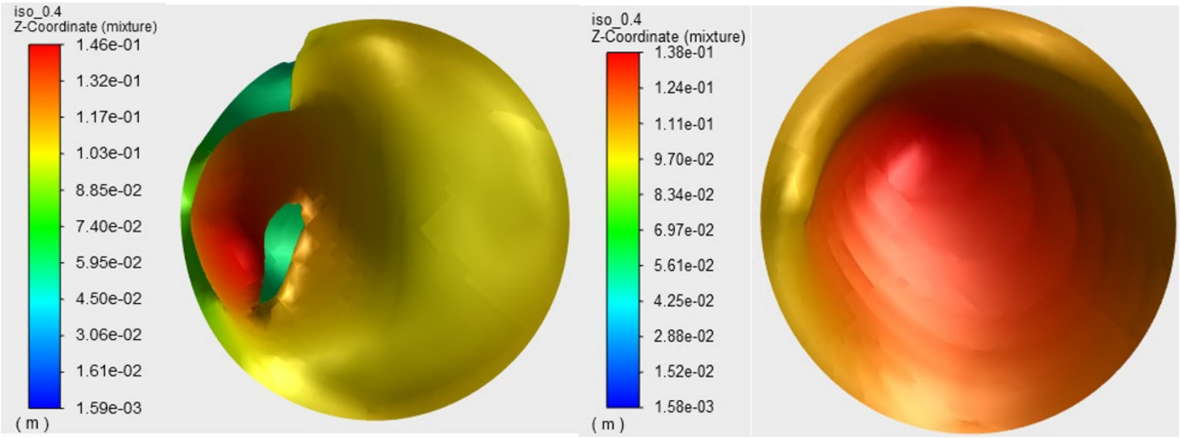


Figure 2. Bed fluctuations frequency.

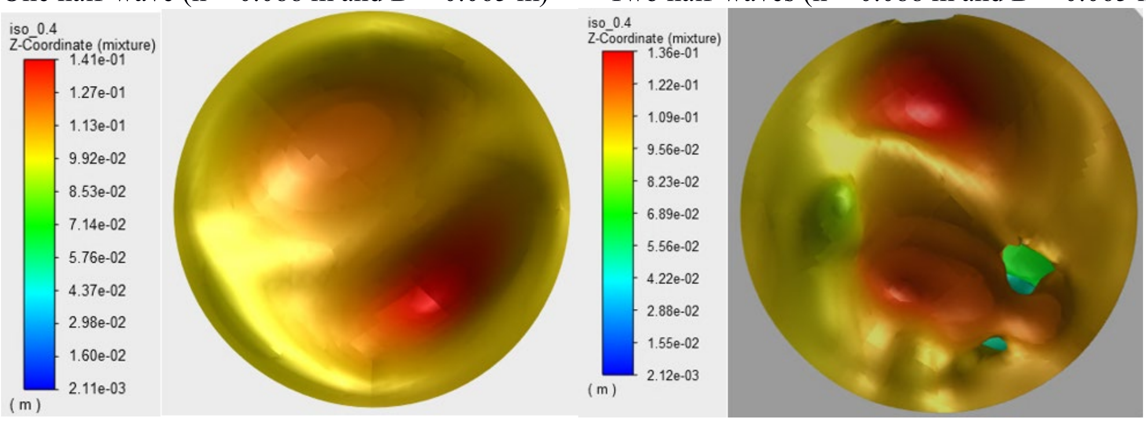
Calculations in Ansys Fluent show that formula (4) is more accurate when the ratio of the diameter to the height is less than 1, and that with an increase in the ratio of the diameter to the height, the number of half-waves along the diameter grows so intensively that, in parallel with this, a smooth increase in the oscillation frequency occurs.

The discrepancy between the modeled frequencies of the bed with the solid lines characterizing the number of half-waves can be explained by the approximation of the analogy used, as well as by the insufficient order of sampling of the solver. It should also be taken into account that the main frequency of the spectrum of pressure fluctuations in the bed depends to a greater extent on the height of the bed [10], and the rate of fluidization velocity also affects the change of fluctuations modes [14].

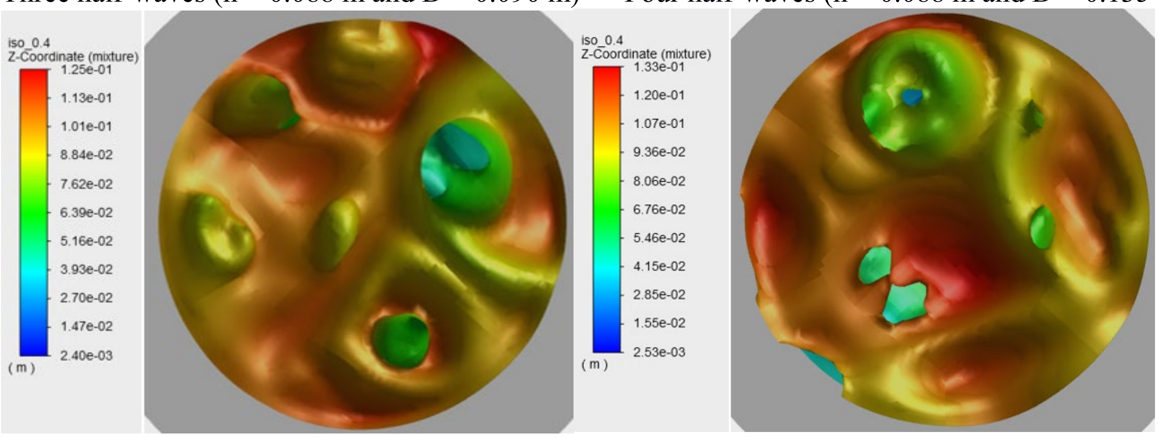
Figure 2 shows the surface of a fluidized bed at different numbers of half-waves (for different geometries).



One half-wave (h = 0.088 m and D = 0.065 m) Two half-waves (h = 0.088 m and D = 0.065 m)



Three half-waves (h = 0.088 m and D = 0.090 m) Four half-waves (h = 0.088 m and D = 0.135 m)



Five half-waves (h = 0.088 m and D = 0.195 m) Six half waves (h = 0.088 m and D = 0.195 m)

Figure 3. Surface of a fluidized bed at different numbers of half-waves.

The isosurface in terms of the volume fraction of solid particles of 0.4 is colored according to the value of the z coordinate (the height of the surface rise). With an increase in the diameter of the installation, the bubbling becomes more intense, and the size of the bubbles relative to the diameter of the installation is smaller.

4. Conclusion

Three-dimensional modeling of a fluidized bed in Ansys Fluent showed that the analogy of the behavior of standing surface waves of an ideal fluid with oscillations of the surface of a fluidized bed can predict an approximate range of possible natural frequencies of fluctuations of a fluidized bed with different geometric parameters. To study the mechanism of changing fluctuations modes, additional studies are needed at different bed heights and fluidization velocity.

Acknowledgments

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