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Simulation of a Pulsating Bed Using Eulerian Approach

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SIMULATION OF A PULSATING BED USING EULERIAN APPROACH

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ABSTRACT

A numerical study of the effect of gas pulsation on the flow pattern of solid particles in a two-dimensional gas-solid fluidized bed was conducted using the Eulerian granular kinetic theory. Our simulated bed dynamics agreed well with the experimental work of Koksal and Vural, and with the Discrete Element Method (DEM) model simulations of Tsuji et al.

INTRODUCTION

Gas-solid fluidized beds are widely used in many industrial processes. One operation in which the gas velocity oscillates analogous to a vibrating bed is called pulsating fluidization. The pulsating fluidized bed was first used to fluidize cohesive particles and served as a method of eliminating slugs and gas channeling, thus improving the quality of fluidization.

Koksal and Vural [1] recently applied pulsation to the fluidized beds of coarse particles, and suggested that the size of the bubbles in the fluidized bed can be controlled by the gas pulsation. Their study also revealed that pulsation produced more uniform fluidization with less bed expansion, thereby improving the gas-solid contact in comparison with continuous flow. Wong and Baird's [2] investigation also showed that pulsation gas flow results in smaller and more uniform bubbles than continuous gas flow. Tsuji et al. [3] developed numerical simulation of pulsating fluidized beds using the Discrete Element Method (DEM).

In this work we studied numerical simulations of pulsating fluidized beds using the Eulerian granular kinetic theory model and Fluent 6.1 computational fluid dynamics (CFD) code. Our numerical simulations predicted the dynamics of the bed reasonably well when compared to the Koksal and Vural [1] experimental results and the DEM simulations of Tsuji et al. [3].

SYSTEM DESCRIPTION

This study comprises two parts. In the first part, we performed simulations of the Koksal and Vural [1] experiment and compared our calculated values with their experimental data. The geometry of the bed, which is a two-dimensional rectangular fluidized bed, is the same as that used by Koksal and Vural [1] in their experiment. The length of the bed is 0.492 m and the height is 1.2 m.

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The properties of the particles used in the simulation are presented in Table 1. Air at a temperature of 300 K was oscillated around its mean velocity at a specified amplitude and different frequencies ranging from 1 to 7 Hz. The magnitude of the velocity was oscillated sinusoidally around the mean velocity, $V_{avg.}$, with the frequency, f_p, and the amplitude, A.

$$V_0 = V_{avg.} + A \sin 2\pi f_p t$$

Initially, the gas and solid velocities were set to zero. The packed bed height was kept at 0.5 m for the turnip seed and 0.45 m for the sand in all of the simulations. Initial solid volume fraction in the bed for the seed particles was 0.48 and for the sand particles was 0.5. The amplitude of pulsation considered for the seed and the sand particles simulations were 0.5 m/s and 0.15 m/s, respectively.

Table 1. Properties of Particles and Calculation Conditions

Material	Diameter (μm)	Density (kg/m^3)	U_{mf} (m/s)	Frequency (Hz)
Turnip Seed	1880	1060	0.80	0, 1, 7
Sand	723	2580	0.46	0, 1, 5

In the second part of our study, we performed simulations of the Tsuji et al. [3] DEM simulations of a pulsating bed, using the Eulerian two-fluid model with the solid phase described by the kinetic theory. Calculation conditions are shown in Table 2.

In this simulation, the fluidized bed had a rectangular shape with the total height of the unit being 0.5 m and a width of 0.2 m using Group B particles [4]. The simulated system was considered to be isothermal at 300 K, and the initial pressure was atmospheric. The inlet gas was oscillated around its mean velocity.

Table 2. Calculation Conditions

Classification	Symbol	Value
Length between periodic boundaries (m)	L	0.2
Initial height of solids patching (m)	H	0.05
Particle diameter (μm)	d	1000
Particle density (kg/m^3)	ρ_s	500
Coefficient of restitution	e_{ss}	0.9
Fluid density (kg/m^3)	ρ_f	1.205
Fluid viscosity (Pa s)	μ_f	1.81e-5
Mean gas velocity (m/s)	$V_{avg.}$	0.3
Amplitude of pulsation (m/s)	A	0.15
Frequency of pulsation (Hz)	f_p	0-8
Time step (sec)	Δt	1e-4
Minimum fluidization velocity (m/s)	U_{mf}	0.14
Solid volume fraction without pulsation	α_s	0.5

MATHEMATICAL MODELING AND NUMERICAL SIMULATION

We used the Eulerian Granular Multiphase (EGM) model [5, 6], based on the kinetic theory approach. The drag force expression of Syamlal et al. [7] was also used in all of our simulations.

In this study, Neumann boundary conditions were applied at the outlet for all of the variables except pressure, which is specified equal to atmosphere pressure. At the inlet, air and solid velocities were specified. The gas distributor was assumed impenetrable for the solid phase by setting the solids axial velocity to zero. Initially, the fluidized bed was set at the minimum fluidization condition. The specified-shear or full-slip wall boundary condition was used for all of the simulations of the Koksal and Vural [1] experiments.

For the DEM simulations, Tsuji et al. [3 used the periodic boundary condition in their simulations, applied in the lateral direction to eliminate the effects of the side wall on the flow field.

The mass and momentum equations for the gas and particulate phases were solved (Eulerian granular approach) using the Fluent 6.1 computational fluid dynamic code. Because of the low Reynolds number of the solid phase, the laminar regime was used for all the simulations. We used transient, quasi two-dimensional equations in the Cartesian coordinates system in our numerical study.

For the simulations of the Koksal and Vural [1] experiments, the computational domain included 98 cells in the X-direction (lateral) and 240 grid cells along the Y-axis (axially). Therefore, a total number of 23,520 computational fluid cells in a Cartesian system of coordinates were used in this simulation.

To compare to theTsuji et al. [3] simulation for Group B particles, the computational domain consisted of 80 cells in the X-direction and 200 grid cells along the Y-axis with a total number of 16,000 computational fluid cells.

The time step of 10^{-4} second was used in all of the simulations. The computational grids were sufficiently fine and further refinement of the grids did not significantly change the average properties, such as bed expansion results, and, hence, we concluded that our calculated results were grid independent.

The governing equations were first discritized on a nonstaggered grid using the finite-volume method and then solved in their algebraic form using the Fluent code.

The second-order discretization technique was used for all of the simulations in order to produce physically realistic bubbles. Finally, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used for the pressure correction calculations.

RESULTS AND DISCUSSION

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Comparison of Our Simulation Results with Koksal and Vural Experimental Data

We performed simulations of the Koksal and Vural [1] experimental work of two-dimensional fluidized bed using a moving double plate distributor. The second plate was placed under the existing distributor such that it could make a reciprocating motion generating pulses to the flow field. In our simulations, we considered the same material properties and did the simulations for different gas flowrate pulsating frequency ranges, at the operating velocity ratio (mean velocity, ($V_{avg.}$) to minimum fluidization velocity, (U_{mf}) of 1.2.

Figures 1, 2, 3, 4 and 5 show the effect of the pulsation on the bubble size and the comparison of our simulation results with the Koksal and Vural [1] experimentally determined bubble diameters. In our simulations, we assumed that a bubble is a region of void greater than 0.85. Our simulation results showed a bubbling behavior similar to that observed experimentally by Koksal and Vural [1] for both the seed and the sand particles.

Similar to the observations made by Koksal and Vural [1], there was a significant reduction in the bubble size in the pulsed flow compared with that in continuous flow due to bubble collapse or bubble splitting in the pulsed flow. For seed particles, the smallest bubbles were formed at the frequency of 5 Hz (see Figure 3), which is similar to that of the Koksal and Vural [1] experimental frequency observations in the range of 4-6 Hz. Figures 3 and 5 show that the bubble collapsing and splitting occurred at intermediate heights. As the pulsation frequency was increased, the effect of pulsation diminished. This is mainly due to the fact that the solid particles in the bed do not have enough time to settle down completely after the bubbles break up.

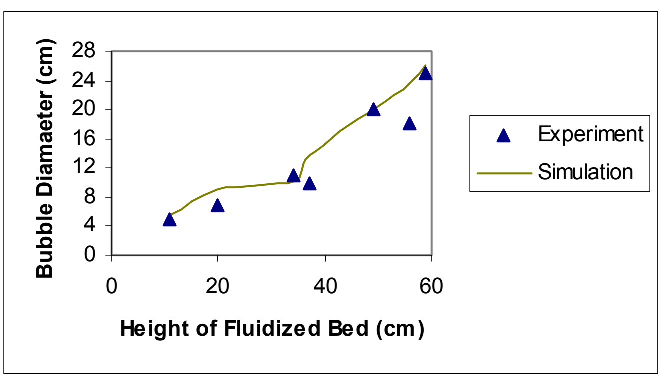

Figure 1. Comparison of our simulated bubble diameter with the experimental measurements of Koksal and Vural with non-pulsated fluidized bed using seed particles of diameter 1880 μm and $V_{avg.} / U_{mf}$ = 1.2

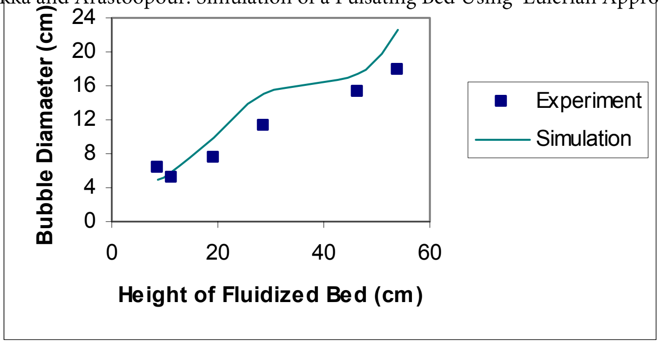

Figure 2. Comparison of our simulated bubble diameter with the experimental measurements of Koksal and Vural with fluidized bed with pulsated gas at a frequency of 1 Hz using seed particles of diameter 1880 μm and $V_{avg.} / U_{mf}$ = 1.2

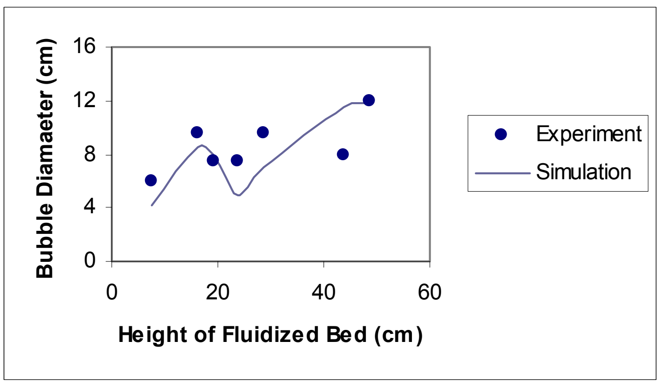

Figure 3. Comparison of our simulated bubble diameter with the experimental measurements of Koksal and Vural with fluidized bed with pulsated gas at a frequency of 5 Hz using seed particles of diameter 1880 μm and $V_{avg.} / U_{mf}$ = 1.2

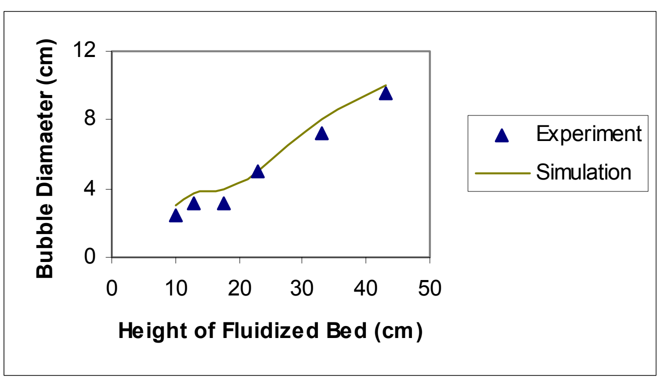

Figure 4. Comparison of our simulated bubble diameter with the experimental measurements of Koksal and Vural with non-pulsated fluidized bed using sand particles of diameter 723 μm and $V_{avg.} / U_{mf}$ = 1.2

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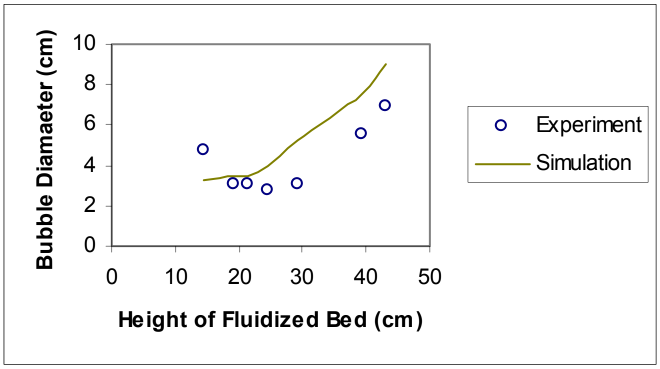


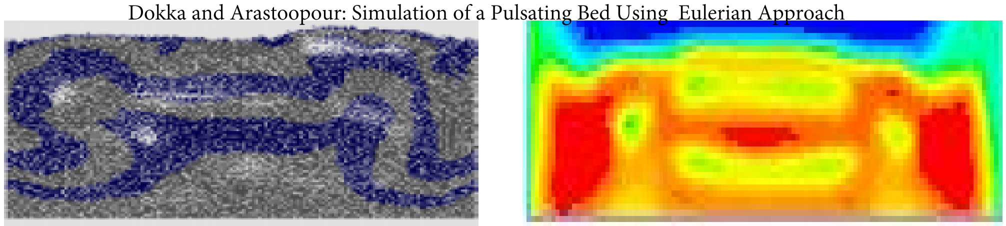
Figure 5. Comparison of our simulated bubble diameter with the experimental measurements of Koksal and Vural with a fluidized bed with pulsated gas at a frequency of 7 Hz using sand particles of diameter 723 μm and $V_{avg.} / U_{mf}$ = 1.2

Our simulation showed that there is a continuous increase in bubble size for both the no-pulse and pulsed-mode cases in the fluidized bed along the bed height (see Figures 1-5). However, pulsed mode data are scattered due to bubble collapse and breakage using both seed and sand particles. This result is similar to the Koksal and Vural [1] experimental data.

Comparison of Our Simulation Results with Tsuji et al. DEM Simulations

Figures 6-8 show the transient variation of the solid volume fraction using our Eulerian Granular Multiphase, EGM, model simulation for a 2D pulsating fluidized bed and comparison with Tsuji et al. [3] DEM simulation at different pulsation frequencies for Group B particles. Our numerical study revealed that the bed behavior and, hence, the bubble size change substantially with pulsation frequency. In all the simulations, the fluidizing gas layer that initially enters the bed forms a single large bubble at the gas distributor that rises to the surface of the bed.

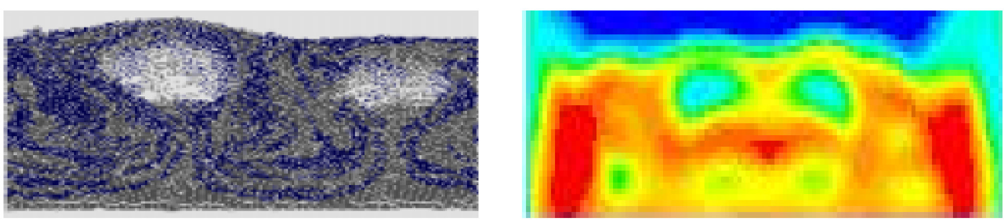
At 0 Hz frequency, our EGM simulation shows a typical bubbling state, in which multiple bubbles were formed in the bed similar to that of the Tsuji et al. [3] simulation. The bubbles initially formed at the distributor plate are large and span the entire width of the bed, but later break into smaller bubbles at intermediate heights (see Figures 6a and 6b). The bubble size, however, is expected to be smaller because of the lack of pulsation.



a) DEM Simulation b) EGM Simulation

Figure 6. Comparison of our EGM simulation for Group B particles at 0 Hz frequency with the DEM simulation of Tsuji et al.

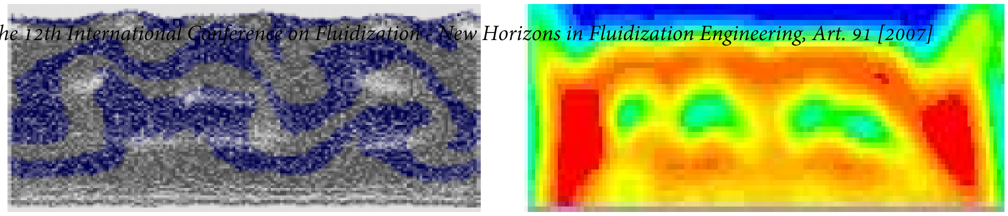
At 5 Hz frequencies, our simulation showed two to three large bubbles varied temporally at different horizontal positions in the bed. The bubbles grew with height and became prominent at higher positions. Most of the bubbles collapsed and split at intermediate heights. The bubbles either completely vanished or split into smaller bubbles. These smaller bubbles coalesced again to form larger bubbles near the surface. The Tsuji et al. [3] simulation showed a similar flow pattern with two large bubbles in the bed forming repeatedly (Figures 7a and 7b).



a) DEM Simulation b) EGM Simulation

Figure 7. Comparison of our EGM simulation for Group B particles at 5 Hz frequency with the DEM simulation of Tsuji et al.

At 8 Hz and higher frequencies, our simulation results showed that the size of the bubbles became small, and the flow patterns for these frequencies were similar to those of the no-pulse mode. This behavior signifies that, as the pulsation frequency is increased, the effect of pulsation diminishes. The major reason for such behavior could be due to the fact that an increase in the rate of pulsation indicates a decrease in the gas shut off time. This means that the solid particles in the bed do not have enough time to settle down completely and break the bubbles. Therefore, the size of the bubbles measured at higher frequencies is comparable with that in a no-pulse mode. Consequently, the response of the granular beds against pulsation becomes neutral in the region of more than 8 Hz frequency for Group B particles. This means that the size of the bubbles does not further increase with the increase in the pulsating gas frequency.



a) DEM Simulation b) EGM Simulation

Figure 8. Comparison between our EGM simulation for Group B Particles at 8 Hz frequency with the DEM simulation of Tsuji et al.

CONCLUSIONS

The Eulerian Granular Multiphase (EGM) model and Fluent 6.1 computer code were used to simulate the effect of gas pulsation in a fluidized bed using two different particle sizes. The numerical results using our model compared well with those of the Koksal and Vural [1] experimental work and the Tsuji et al. [3] DEM model.

Our simulations showed that in a fluidized bed using Group B particles, there is a continuous increase in the bubble size from the no-pulse frequency mode to a lower frequency range, and there is no significant bubble growth for the 4 and 5 Hz due to extensive bubble collapsing and splitting. At 8 Hz and higher frequency ranges, the gas pulsation stabilizes the bubble formation and the bubble size becomes smaller.

In summary, for pulsating bubbling fluidized beds, our EGM approach, which is based on the kinetic theory, was able to simulate the fluidization of Group B particles. Experimentally verified expression for particle interaction is needed to be included in the model for quantitative description of the fluidization parameters.

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