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An Experimental Study on Effects of Applying the Pulsating Flow to a Gas-Solid Fluidized Bed

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Abstract**—**There have been widespread applications of fluidized beds in industries which are related to the combination of gas-solid particles during the last decade. For instance, in order to crack the catalyses in petrochemical industries or as a drier in food industries. High capacity of fluidized bed in heat and mass transfer has made this device very popular. In order to achieve a higher efficiency of fluidized beds, a particular attention has been paid to beds with pulsating air flow. In this paper, a fluidized bed device with pulsating flow has been designed and constructed. Size of particles have been used during the test are in the range of 40 to 100µm. The purpose of this experimental test is to investigate the air flow regime, observe the particles' movement and measure the pressure loss along the bed. The effects of pulsation can be evaluated by comparing the results for both continuous and pulsating flow. Results of both situations are compared for various gas speeds. Moreover the above experiment is numerically simulated by using Fluent software and its numerical results are compared with the experimental results.

Keywords**—**Fluidized bed, pulsating flow, gas-solid particles, pressure loss, experiments, Fluent.

I. INTRODUCTION

FLUIDIZATION is an operation by which an assemblage of solid particles is transformed into a fluid-like state through contact with a flowing gas or liquid. Fluidized beds have considerable advantages for material processing and are used in numerous important industrial applications Kunii and Levenspiel [1]. Fluidization occurs when particulate materials are suspended in up moving gas. In this situation, friction forces between particles and gas flow will neutralize particles' weight. This bed is called as minimum fluidized bed. With increase in velocity rate to a rate of more than minimum fluidization velocity, large instability with bubbling will be observed by gas flow in the bed. In higher velocities, the flow turbulence and movement of particles become more violent. This kind of bed mentioned as bubbling fluidization bed. In gas-solid systems, these bubbles join each other while rising and produce larger bubbles.

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In this investigation, the use of pulsating flow in fluidization bed has been experimentally probed. The purpose of pulsating flow usage is to control the bubbles' behavior and prevent their generation. With an increase in gas flow velocity to a rate above minimum fluidization velocity, the production of bubbles is inevitable. Bubbles' rising will cause an expansion in the bed; besides, circulation of gas and particles around these bubbles will lead to a decrease in the contact between the gas and the particles. Therefore, a reduction in heat transfer will be observed which is equal to a lower efficiency. The other problem which will be arisen with generation of bubbles is the explosion of bubbles on the bed's wall which cause erosion.

The primary studies about fluidized bed with pulsating flow were carried out by Massimilla et al. [2]. They classified the pulsating flow in order of mean pressure drop in different frequencies. Kobayashi et al. [3] showed that the expansion of pulsating bed will be grown by an increase in velocity; furthermore, will be reduced by a reduction in time connection (t_{on}).

Wong and Baird [4] investigated the production of pulsating flow by bed's vibration. The common result in all these probations were the considerable increase of heat transfer in fluidized bed with pulsating flow for a range of 30-40%. Zhang and Koksal [5] showed that the use of pulsating flow will cause a reduction in bubbles' diameter; also, the number and diameter of bubbles will be reduced by a decrease in t_{on}. Chyang and Lin [6] proved that in order to achieve the maximum heat transfer in a bed consisted of particles with diameter less than 100µm, the sum of t_{on} and t_{off} should be less than 1 second.

In this study, a pulsating fluidized bed has been constructed in order to observe the particle's movements, air flow regime and pressure drop through a bed by using a pulsating mechanism which creates various frequencies.

II. BASIC THEORY

The first step in the procedure of beds designing is calculating the effective diameter of particles. There are variety of techniques, introduced by Zens and Othmer [7], to measure the equivalent diameter of non-spherical particles. The sphericity, Φ_s, defined as

$$\Phi_s = \left(\frac{surface\ of\ sphere}{surface\ of\ particle}\right)_{of\ same\ value} \tag{1}$$

Where $\Phi_s=1$ is for sphere and $0<\Phi_s<1$ for other particles. In our experiment Φ_s is taken to be 0.8. To represent a bed of non-spherical particles by a bed of spheres of diameter d_{eff} such that the two beds have the same total surface area and the same fraction voidage ε_m. One should ensure almost the same frictional resistance to flow in these two beds. Since there is no general relationship between d_{eff} and d_p, the best way to calculate the d_{eff} for irregular particles with no seemingly longer or shorter diameter is the following equation.

$$d_{eff} = \phi_s d_{sph} = \phi_s d_p \qquad (2)$$

The frictional pressure drop, always positive, through a fixed bed containing a single size particle with d_p and can been calculated by equation of Ergan [8]

$$\frac{\Delta P_{fr}}{L_m} = 150\frac{(1-\varepsilon_m)^2}{\varepsilon_m^3}\frac{\mu \times u_0}{(\phi_s d_p)^2} + 1.75\frac{1-\varepsilon_m}{\varepsilon_m^3}\frac{\rho_g}{} \qquad (3)$$

The measured pressure drop along the bed can be calculated as

$$\Delta P_{measured} = \Delta P_{fr} \pm \frac{\rho_g L_m}{g_c} \qquad (4)$$

In which the positive sign is for upward flow of fluid. The last term in above equation can be withdrawn in case of beds with gas flow. Furthermore, ε_m, related to sphericity, can be calculated using the graphical plot which was introduced by Yates [9].

As mentioned earlier, in a bed under influence of a upward flow, fluidization occurs when weight of particles is equal with the drag force by upward moving gas, so

$$\Delta P_b A_t = W = A_t L_{mf}(1-\varepsilon_{mf})\left[(\rho_s - \rho_g)\frac{g}{g_c}\right] \qquad (5)$$

Furthermore, minimum fluidizing velocity (u_{mf}) can be calculated by combining Eq. 4 with Eq.5 and follows

$$\frac{1.75}{\varepsilon_{mp}^3 \phi_s}\left(\frac{d_p u_{mf}\rho_g}{\mu}\right)^2 + \frac{150(1-\varepsilon_{mf})}{\varepsilon_{mp}^3 \phi_s^2}\left(\frac{d_p u_{mf}\rho_g}{\mu}\right) = \frac{d_p^3 \rho_g(\rho_s-\rho_g)g}{\mu^2} \qquad (6)$$

The fluidization velocity at which bubbles are first observed is called the minimum bubbling velocity, u_{mb}. For a bed including small size particles e.g. 5-100 µm, with increasing gas velocity beyond u_{mf}, the bed expands smoothly. However, at a gas velocity of about 3umf, bubbles begin to form and bed height begins to decrease.

Geldart and Abrahamsen [10], [11] measured u_{mb} for 23 different particles (ρ=1.1-4.6 g/cm³, d_p =20-72 µm), using ambient air, helium, argon, carbon dioxide and Freon-12. They found that u_{mb}/u_{mf} was strongly dependent on the weight fraction of particles size smaller than 45 µm, and for these systems. They introduced the following relation

$$\frac{u_{mb}}{u_{mf}} = \frac{2300\rho_g^{0.13}\mu^{0.52}exp(0.72P_{45\,\mu m})}{\overline{d_p}(\rho_s-\rho_g)^{0.93}} \qquad (7)$$

When a particle of size d_p falls through a fluid, its terminal free-fall velocity (u_t) can be estimated from fluid mechanics by the expression

$$u_t = \left[\frac{4d_p(\rho_s-\rho_g)g}{3\rho_g C_D}\right]^{\frac{1}{2}} \qquad (8)$$

Where, C_D is an experimentally determined drag coefficient. To calculate the terminal velocity, a graphical plot represented in Haider et al. [12] which has been used to allows a direct evaluation of u_t by given d_p and the physical properties of the system.

III. Test Apparatus

One of the goals of this experiment is to investigate a pulsating flow hydrodynamics. The main components of the apparatus are listed below:

Hollow cylinder constructed by the material of phlexy glass with dimensions of 11 cm inner diameter and height of 50 cm

Paper air filters placed on the bottom of cylinder to put the particles on and top of it to prevent particles from leaving the bed. Diameter of the filters is 15 cm consist of tiny holes with 40 µm opening.

Flanges of phlexy glass to connect different parts of the apparatus and fix the filters.

Solenoid valve and electrical-control circuit to produce pulsating flow with various on and off times (see Fig 1).

Measurement devices consist of a monometer to measure the pressure drop and a turbine velocity meter to measure air velocity.

Test particles are in C and A group according to Geldart [10] classification.

Design details of the bed are shown in Fig. 2.

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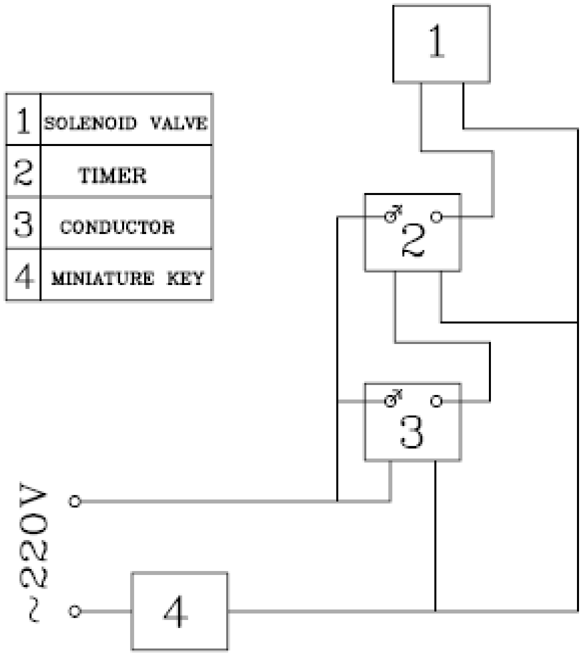

Fig. 1 Schematic design of the circuit

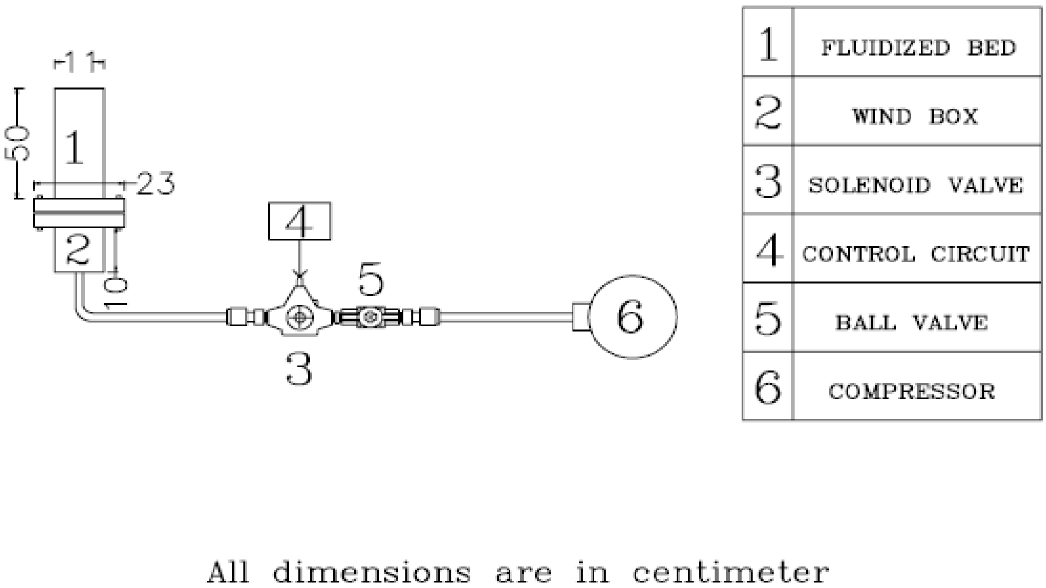

Fig. 2 Schematic design of the apparatus

IV. Results and Discussions

The test is carried out with two kinds of particles. Tetraborate decahydrate and potassium sulfate with characteristics of: Q_s=0.85, d_p=40-50μm, ρ=1.72gr/cm^2, ε_m=0.41, Q_s=0.85, d_p=100μm, ρ=2.66gr/cm^2, ε_m=0.4 respectively. Air properties are assumed to be: $\mu=1.85\times10^{-5}$ N.s/m^2, ρ_g=1.115Kg/m^3.

The height of bed, primary thickness of particles' pack, is taken to be 3 cm in all experiment. Calculated results using the theoretical equations for both sorts of particles have been shown in the Table 1. These results have been used for both estimation of beds physical dimensions and verification of the outcomes of experimental test.

Table 2 represents the results of the experimental test for a continuous air flow at velocity of 0.1 m/s. Comparing values of calculated result from Table 1 with the experimental finding, an error of 4.6% for Tetraborate decahydrate and 6.4% for Potassium sulfate can be find. This shows a good agreement with our assumptions. Although, there can be some errors due to experiment and instruments.

TABLE I
THEORETICAL CALCULATION OF FLUIDIZED BED'S PARAMETERS

Tetraborate decahydrate	Potassium sulfate
u_{mf} = 0.0105cm/s	u_{mf} = 0.674 cm/s
Re = 2.84×10^{-4}	Re = 0.041
u_{mb} = 0.766 cm/s	u_{mb} = 0.766 cm/s
u_t = 6.33 cm/s	u_t = 0.583 cm/s
ΔP_b =3.04 mH_2O	ΔP_b = 4.7 cmH_2O

TABLE II
PRESSURE DROPS FOR A CONTINUOUS AIR FLOW WITH VELOCITY OF 0.1 M/S

Tetraborate decahydrate	Potassium sulfate
ΔP_b = 2.9 cmH_2O	ΔP_b = 4.4 cmH_2O

After pressure drop verification, the second step is the experimental measurement of the pressure drop for a pulsating air flow. Fig. 3 and Fig. 4 illustrate the pressure drop for different time on and off in ranges of 1 to 3 seconds. It can be easily observed that for a constant t_{on} , there is an increase in the pressure drop while the t_{off} is increased. Fig. 5 shows comparison of the pressure drops data for various velocities at two cases of pulsating flow with frequencies of 0.5 and 1 Hz and continuous flow. According to the results, for pulsating flows with smaller t_{on} the pressure drop is higher, the reason for this phenomenon lies in the similarity between currents with higher t_{on} and continuous flow. In addition, in case of smaller t_{off}, particles not allowed to drop down and destroy the incoming bubbles which are similar to what happens in the continuous flows.

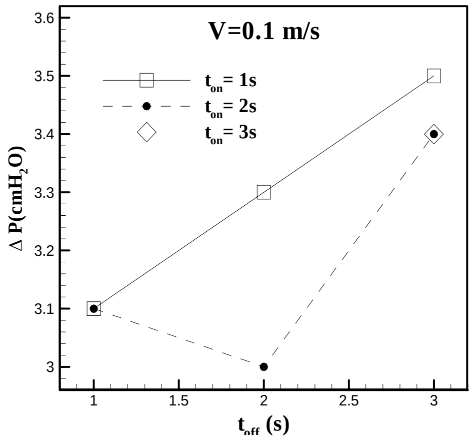

Fig. 3 Pressure drop of Tetraborate decahydrate

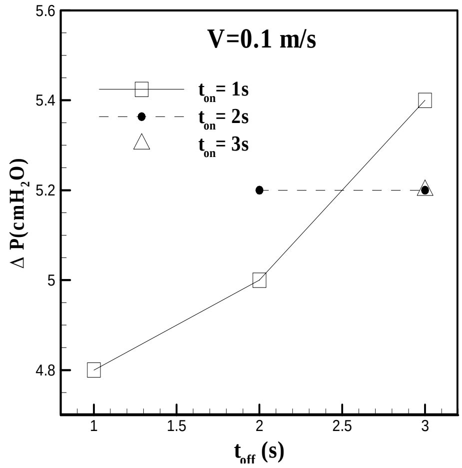

Fig. 4 Pressure drop of Potassium sulfate

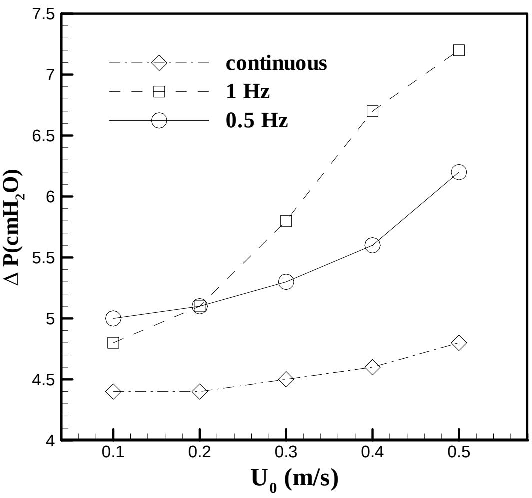

Fig. 5 Comparison of pressure drop of continuous and pulsating for Potassium sulfate

Moreover, the experiment is numerically simulated by using the Fluent software. The simulation is preformed for continuous air flow in a vertical cylinder with velocity of 0.1 m/s. All parameters used in the simulation are the same as the experiment. Fig. 6 illustrates the results for pressure drop using the software. According to Fig. 6, the Pressure drop along the bed calculated by the software is 255Pa which is equal to 2.6 cmH_2O. This demonstrates an error of 10.3% and 14.5% with experimental and theoretical calculations for Tetraborate decahydrate particles respectively. Fig. 7 displays the bed height and the flow regime.

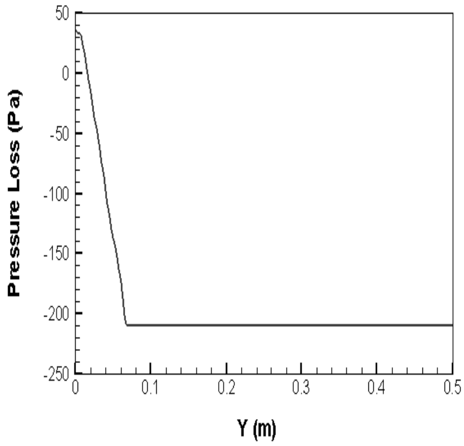

Fig. 6 pressure drop through the bed

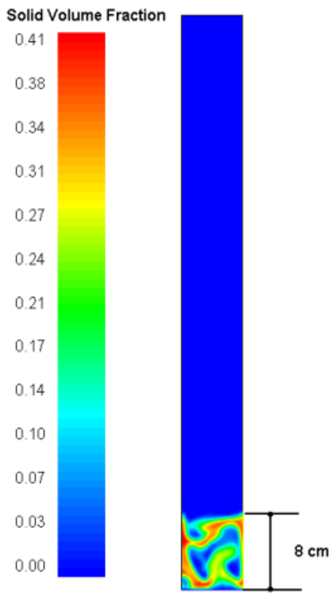

Fig. 7 particles' distribution along the bed

V. Conclusions

A pulsating flow fluidized bed was constructed in this study. Further measured data of continuous flow test were compared with theory and results of simulation of the same bed using the software. Moreover, for the pulsating flow, it was shown with reduction in t_{on} and t_{off} of the inlet air, an increase in the pressure drop can be seen through the bed. With comparison between continuous and pulsating flow, it can be observed that the pressure drop is higher in pulsating flow. Finally, as it was expected from theory with an increase in inlet air velocity, the pressure drop rise with a growing rate. The reason of this phenomenon is growth of bubbles' production due to increase in flow velocity. However, use of pulsating flow can reduce bubbling.

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