Effect of Particle Size Distributions on Minimum Fluidization Velocity with Varying Gas Temperature

Krittin Korkerd, Chaiwat Soanuch, Pornpote Piumsomboon, and Benjapon Chalermsinsuwan

***Abstract*—The particle size distribution (PSD) is an important property that can influence the hydrodynamics and chemical conversion in fluidized bed system. The objective of this study is to investigate the effect of PSDs of particle and gas temperature on minimum fluidization velocity (U_{mf}). Here, the silica sand with three average diameters and five PSDs including narrow cut, Gaussian, Gaussian with high standard deviation, negative skewed distribution and positive skewed distribution were used. The considered gas temperature ranged from 30 to 120 °C. The results showed that the U_{mf} values with wide PSDs were lower than the U_{mf} values for narrow cut particle with the same average diameter. The reason can be explained by the addition of smaller particle will improve the fluidization characteristics. The standard deviation and skewness of PSD also influenced on the U_{mf}. The U_{mf} was observed to decrease with increasing gas temperature. In addition, the effect of average particle diameter could also be seen. The U_{mf} increased with the increasing of average particle diameter.**

***Index Terms*—Gas-solid fluidization, minimum fluidization velocity, particle size distribution, gas temperature.**

I. Introduction

Nowadays, fluidization technology is used in many physical and chemical industrial processes, such as drying, combustion, gasification and catalytic cracking because of its advantage characteristics including system well-mixing, large contacting surface area, high heat transfer rate and etc. Therefore, the understanding of hydrodynamics is required for designing and operating the fluidized bed process. There are many operational and geometrical parameters that affect the hydrodynamics behavior of fluidized bed process. Among them, one of the most important parameters for the suitable design and operation is minimum fluidization velocity (U_{mf}) which is defined as the superficial gas velocity at which the drag force of the upward moving gas is equal to the weight of the solid particle. Then, all the solid particles are suspended [1]. This parameter depends on properties of solid and fluid, including system operating conditions. Therefore, the variation of the U_{mf} under a variety of conditions should be study.

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With the application of fluidized bed process in real industry, such as circulating fluidized bed (CFB) boiler, the fuel particles which have average diameter value in the range of 1 to 1.5 mm accounts for only 1-3 % by weight of total solid particles, while the other medium particles especially sand particles are in majority [2]. Many literature researches then used sand as the main material to study the hydrodynamics in fluidized bed process. Matheson *et al.* [3] found that fluidization of large narrow cut particles had bad quality while adding fine particles into the bed could improve the fluidization behavior, called as lubricating effect. However, the particle size was not the only parameter that influenced on the hydrodynamics but the particle size distribution (PSD) might also play an important role in the fluidization behavior [4], [5]. Sun and Grace [6] studied the effect of PSD on fluidization characteristics. They found that the effect of wide PSD on the fluidization behavior and chemical conversion would not significantly observe until the gas velocity exceeded 0.2 m/s. Though, this effect was not observed when the system was fluidized with narrow cut particles. As a consequence, the PSD could influence the hydrodynamics and chemical conversion in fluidized bed process [7].

Several studies had focused on the effect of PSDs on U_{mf}. Gauthier *et al.* [8] investigated the effect of PSDs including narrow cut, Gaussian, binary mixture, and flat type with similar average particle diameter on the U_{mf}. They pointed out that Gaussian and narrow cut particle distributions had nearly the same U_{mf}. Moreover, the U_{mf} of binary mixture and flat size distributions were similar but different from the Gaussian type and narrow cut particle distributions. Rasteh *et al.* [9] studied the effect of various PSDs on U_{mf} in tapered fluidized bed. The binary mixture and flat size particle distributions fluidized at the higher gas velocities and the Gaussian distribution particle fluidized at the lower gas velocities comparing to narrow cut particle distribution. Jiang *et al.* [2] used wide PSDs with skewed distribution as bed material to investigate the effect of PSDs on the fluidization behavior. The particles of heavy skewed distribution sloped to smaller size were the easiest to fluidize. Moreover, the U_{mf} increased in the order of heavy skewed distribution sloped to larger size, light skewed distribution sloped to smaller size and Gaussian type distribution.

Because the temperature inside the fluidized bed process was not constant depending on the employed applications, many researchers thus studied the effect of temperature on the U_{mf}. The U_{mf} decreased with increasing system temperature for all average diameter of solid particles which can be attributed to the variation of gas viscosity with system temperature [10], [11]. Lin *et al.* [12] explored the effect of system temperature in the range of 700 to 900 °C with PSDs

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on the U_{mf}. They found that the U_{mf} of binary mixture and flat type distribution behaved similarly. Jiliang *et al.* [13] also found that the system temperature and PSDs significantly affected the U_{mf}. However, the skew PSDs along with varying average particle diameter and gas temperature are still not investigated in the literature experimental or numerical studies.

Therefore, this study aimed to study the effect of various PSDs with variation of gas temperature on the U_{mf} in a fluidized bed reactor. The experimental study was conducted at temperatures ranging from 30 to 120 °C with silica sand having three average particle diameter and five different PSDs including narrow cut, Gaussian, Gaussian with high standard deviation, negative skewed distribution and positive skewed distribution.

II. Experimental

A. Experimental Set up

The schematic setup for the experiments is shown in Fig. 1. The fluidized bed reactor was a stainless steel column with an internal diameter of 12.5 cm and a height of 50 cm. At the base of the reactor column, the stainless steel porous plate having 10.1 % open area was used as the gas distributor, which located directly below the mesh of 250 (sieve size: 0.051 mm) to obtain uniform fluidization and avoid solid particle leakage. The porous plate was placed on an air box with the height of 7 cm. The air was fed into a bottom of column through a compressor. The flow rate of air was measured by three rotameters with the ranges of 0 to 100 L/min, 0 to 300 L/min and 0 to 1,600 L/min. To adjust the temperature of air before entering to the column, the air was first introduced into a preheater, which regulated the heating rate and maintained the temperature to a desired value.

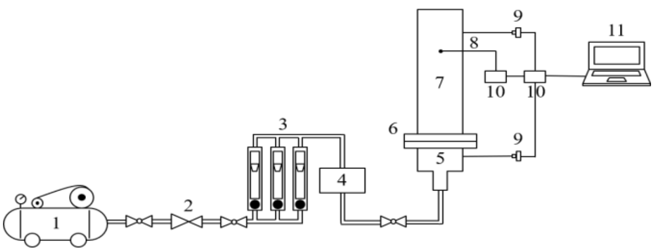


Fig. 1. Schematic diagram of the experimental setup used in this study: (1) compressor, (2) pressure regulator, (3) rotameters, (4) preheater, (5) wind box, (6) gas distributor, (7) fluidized bed reactor, (8) thermocouple, (9) pressure sensors, (10) data loggers and (11) computer with data analyzing software.

A K-type thermocouple was inserted into a column (40 cm above the gas distributor) to measure the air temperature. The pressure drop was measured using pressure sensors. There were two pressure ports which were located between the air box and the freeboard of the reactor column (30 cm above the gas distributor) to measure the absolute pressure. The measuring air temperature and pressures were collected by a data logger. The data were used to calculate pressure drop in a personal computer. In addition, the actual air velocity was measured above gas distributor by an air velocity meter to verify the obtained flow rate.

B. Material

Silica sand was used as the bed materials. The density of this solid particle was 2,650 kg/m^3. To study the effect of PSDs on the U_{mf}, three different average particle diameters (0.19 mm, 0.46 mm and 0.92 mm) belonging to Geldart groups B and D and five types of PSD (narrow cut, Gaussian, Gaussian with high standard deviation, negative skewed distribution and positive skewed distribution) for each average particle diameter were studied. These PSDs were prepared by mixing of the specific amount of particle between two successive standard sieves from a sieving shaker according to the method suggested by Gauthier et al. [8]. As an example, the PSDs for solid particles with an average particle diameter of 0.19 mm are shown in Fig. 2. The wide PSDs were controlled to have the same average diameters (d_p) as the narrow cut particle by Eq. (1):

$$d_p = \frac{1}{\sum_i (x_i / d_i)} \tag{1}$$

where x_i is the mass fraction of particle having size d_i.

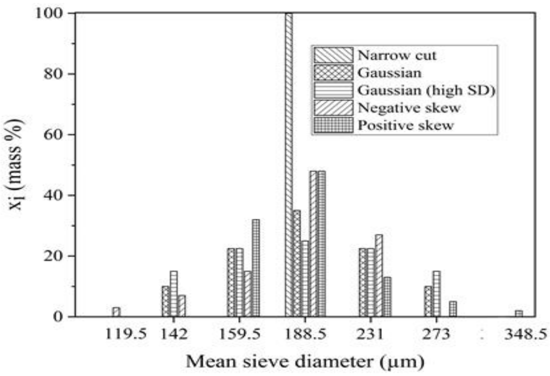


Fig. 2. Different PSDs of solid particles with average particle diameter of 0.19 mm.

C. Procedure

In this experiment, the system was filled by 2 kg of prepared particles in order to maintain the amount of bed for each experiment. Air was passed through the preheater to heat to the desired temperature of 30, 75 and 120 °C as measured by thermocouple. After the air temperature reached a desired value, the air flow rate was reduced to zero and then started the fluidization experiment. The increasing of air flow rate was adjusted carefully by regulated rotameter. Then, the pressure drop was recorded until a full fluidization phenomenon corresponding to a constant system pressure drop was found.

To determine the value of U_{mf}, a typical curve which plotted the pressure drop (ΔP) versus superficial gas velocity (U_0) that was measured by the air velocity meter was examined as shown in Fig. 3. For PSDs, the U_{mf} was determined by an intersection point of the fixed bed line and the complete fluidized line. The fixed bed line was a line fitted to the pressure drop data in the fixed bed state while the complete fluidized line was a line fitted to the constant pressure or fluidized bed state. From fluidization theory, in fixed bed state, the pressure drop is increased with increasing superficial gas velocity due to the friction between particles, while, in fluidized bed state, the pressure drop is constant with increasing superficial gas velocity because the particles are started to suspend and separate from each other. For the deviation from the straight line, it is because the different fluidization behavior of each particle in PSDs.

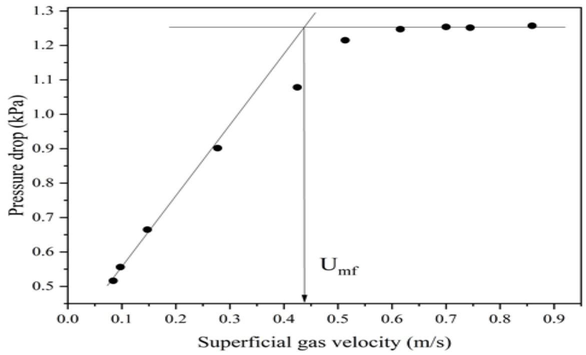


Fig. 3. The example of pressure drop versus superficial gas velocity for Gaussian type distribution.

III. Results and Discussion

A. Effect of PSDs on Minimum Fluidization Velocity

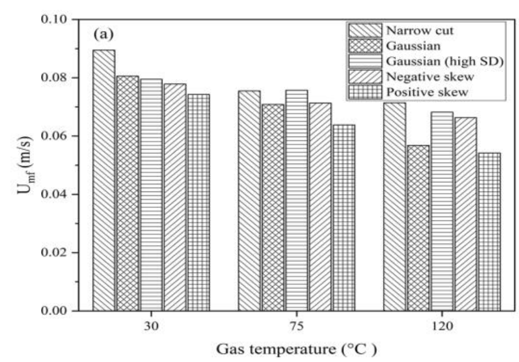
Table I shows the experimental details and the value of the U_{mf} for each case of the experiment. The comparisons of the U_{mf} values for narrow cut, Gaussian, Gaussian with high standard deviation, negative skewed distribution, and positive skewed distribution which have the same average diameters are shown in Fig. 4.

In this section, 30 °C gas temperature was considered. It can be seen that the U_{mf} of the wide PSDs were lower than the narrow cut particle for the entire employed average particle diameter in this study. This can be explained by the lubricating effect of smaller particle as suggested by Matheson *et al.* [3]. The addition of smaller particles in the system will improve the fluidization behavior and will make the solid particles to be well mixed. First, the small particles are fluidized and collided with the large particles thereby reducing the friction force. Then, the drag force of the large particles is increased which causes the bed to fluidize at a lower gas velocity than the narrow cut particle. This results agreed with the studies of Gauthier *et al.* [8], Rasteh *et al.* [9], Lin *et al*. [12] and Feng *et al.* [14].

TABLE I: Experimental Results for Minimum Fluidization Velocity of Various PSDs

Average particle diameter (mm)	PSD (-)	Temperature (°C)	U_{mf} (m/s)
0.19	Narrow cut	30	0.089
		75	0.075
		120	0.071
	Gaussian	30	0.081
		75	0.071
		120	0.057
	Gaussian (high SD)	30	0.079
		75	0.076
		120	0.068
	Negative skewed	30	0.078
		75	0.071
		120	0.066
	Positive skewed	30	0.074
		75	0.064
		120	0.054
0.46	Narrow cut	30	1.050
		75	0.740
		120	0.560
	Gaussian	30	0.980
		75	0.700
		120	0.530
	Gaussian (high SD)	30	0.920
		75	0.680
		120	0.540
	Negative skewed	30	0.830
		75	0.660
		120	0.510
	Positive skewed	30	0.760
		75	0.610
		120	0.500
0.92	Narrow cut	30	3.190
		75	2.690
		120	2.480
	Gaussian	30	3.000
		75	2.230
		120	2.120
	Gaussian (high SD)	30	2.980
		75	2.310
		120	2.140
	Negative skewed	30	2.940
		75	2.450
		120	2.200
	Positive skewed	30	2.920
		75	2.270
		120	2.130

For the comparing of U_{mf} of Gaussian and Gaussian with high standard deviation types, the overall trend of U_{mf} values of Gaussian with high standard deviation type was lower than the overall trend of U_{mf} values of the Gaussian type. As stated above, having more smaller solid particles can help the fluidization to be easier even though Gaussian with high standard deviation type particle had larger particles than Gaussian type. For the case of skewed distribution, the negative skewed distribution had the particles sloped to larger size and the positive skewed distribution had the particles sloped to smaller size. These two distributions were controlled to have the same average particle diameter as the Gaussian type for comparing the effect of PSDs on U_{mf}. However, it could not use the particles of the same sieved size as the Gaussian type. From statistics, the mean for a negative skewed distribution is greater than the mean for a normal distribution (or Gaussian type) and the mean for normal distribution is also greater than the mean for a positive skewed distribution. Therefore, the sieved size particles were adjusted in the skewed distributions to control the average particle diameter as the Gaussian type as can be seen in Fig. 1.



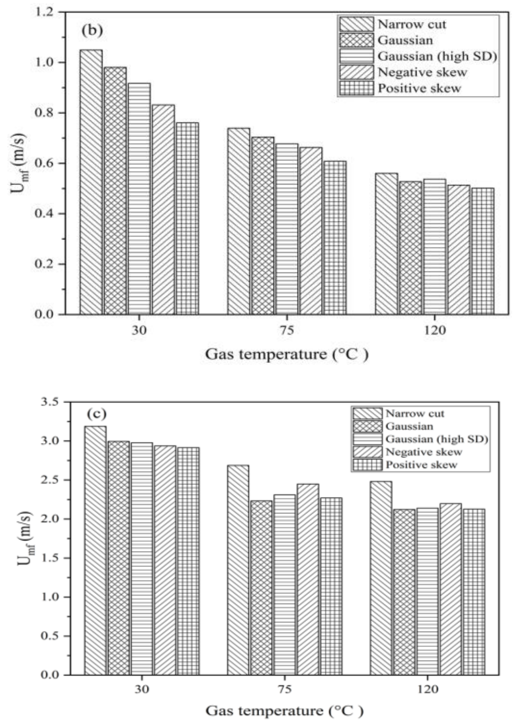


Fig. 4. Experimental results of U_{mf} values for various PSDs: (a) 0.19 mm, (b) 0.46 mm and (c) 0.92 mm.

The U_{mf} of Gaussian type was larger than those of two skewed distributions and the U_{mf} of negative skewed distribution was higher than that of positive skewed distribution. The reason is that the negative skewed distribution has smaller particles greater than the particles in the Gaussian type. The U_{mf} of positive skewed distribution was lower than the U_{mf} of negative skewed distribution even though it had a few proportions of larger particles. However, the positive skewed distribution has more proportions of smaller particles. This study obtained results of skewed distributions were not in agreement with Jiang et al.'s study [2]. This is because, in their study, the U_{mf} of skewed distribution was examined with different average particle diameter.

B. Effect of Gas Temperature on Minimum Fluidization Velocity

The effect of gas temperature on the U_{mf} is illustrated in Fig. 4. The U_{mf} decreased with increasing air temperature for all the PSD types and average particle diameters. The results agreed with the results of Lin *et al.* [12], Jiliang *et al.* [13] and Bruni *et al.* [15]. Moreover, the finding of Goo *et al.* [16] and Subramani *et al.* [17] found that for average particle diameter less than 2 mm, the U_{mf} decreased with increasing temperature related to the variation in gas density and viscosity with temperature. The gas viscosity increases while its density decreases as increasing gas temperature. The variation of viscosity then effects on drag force through the stokes' law [18]. This leads to an increasing of drag force, making the viscosity-related losses for the fluidizing medium, and causing particle to fluidize easier. When the gas temperature increased, the trends of U_{mf} were affected by PSDs for each average size of particle.

For average particle diameter of 0.19 mm, the U_{mf} of narrow cut particle was greater than that of the wide PSDs. However, when comparing between the U_{mf} of Gaussian and Gaussian with high standard deviation types, it found that the U_{mf} of Gaussian with high standard deviation type was greater than that of Gaussian type. This is different from the result at gas temperature of 30 °C. When comparing between the U_{mf} of Gaussian and skewed distributions, it was found that the U_{mf} of negative skewed distribution was greater than that of Gaussian and positive skewed distribution, respectively. The results were also different from the results at temperature of 30 °C.

For average particle diameter of 0.46 mm, the trends of U_{mf} values for every PSD types at gas temperature of 75 °C were the same as the trends at gas temperature of 30 °C. But, at the temperature of 120 °C, the U_{mf} values for all wide PSD had nearly similar values and less than the U_{mf} value of narrow cut particle.

For average particle diameter of 0.92 mm, at the temperature of 75 °C, the U_{mf} of narrow cut particle was higher than that of the wide PSDs. When comparing between the U_{mf} of Gaussian and Gaussian with high standard deviation type, it was found that the U_{mf} of Gaussian with high standard deviation type was greater than that of Gaussian type. For the U_{mf} of Gaussian and skewed distributions, it was found that the U_{mf} of skewed distributions was greater than that of Gaussian distribution. However, at temperature of 120 °C, the U_{mf} values for all wide PSDs had nearly similar values and less than the U_{mf} value of narrow cut particle.

From all the obtained results, it showed that the dependence of the U_{mf} with gas temperature was strongly affected by average particle diameter. As can be seen in Figure 4, the U_{mf} increased with increasing average particle diameter for all the PSD types and gas temperature. With the reason suggested by Downmore *et al.* [11], when the small and large particle were packed with the same height of reactor column, the bed of large particles had a higher void fraction. This indicated that the created pressure drop across the bed of large particles was lower compared to smaller particles. In addition, the weight for the bed of smaller particles was greater than that for the larger particles. It indicates the higher viscous drag force [19], [20]. This resulted in the U_{mf} of large sized particle to be larger than that for the small sized particle.

IV. Conclusion

This study investigated the effect of PSD on the minimum fluidization velocity over a gas temperature range of 30 to 120 °C. The silica sand with three average particle diameters (0.19, 0.46, and 0.92 mm) and five particle size distributions (narrow cut, Gaussian, Gaussian with high standard deviation, negative skewed distribution, and positive skewed distribution) were used in the experiments. The experimental data showed that the PSD had a great effect on the minimum fluidization velocity. The wide PSDs fluidized at the lower superficial gas velocities comparing to narrow cut particle with the same average particle diameter. This is due to the lubricating effect of smaller particles in the system which improves the fluidization behavior. The addition of smaller particles can increase the drag force of large particles. Then, the bed of PSDs can fluidize at a lower gas velocity. The standard deviation of the distribution influenced on the U_{mf}

that the U_{mf} of Gaussian with high standard deviation type was lower than the values of the Gaussian type. The skewness of distribution also influenced the U_{mf} that the U_{mf} of two skewed distributions were lower than the Gaussian type. The U_{mf} of negative skewed distribution was greater than that of positive skewed distribution. For the increasing of gas temperature, the minimum fluidization velocity decreased for all the average particle diameters due to the increasing of gas viscosity. Moreover, the average particle diameter was also had an influence on the U_{mf}. The U_{mf} increased with the increasing of average particle diameter for all the PSDs and gas temperatures. Therefore, when dealing with the applications of fluidized bed reactor in the real industry, the influence of the PSD and temperature could be considered. For the future study, the obtained data will be used to develop the drag force model for using in the simulation of fluidized bed reactor with PSD's particle.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

K. Korkerd conducted the research; All authors had analyzed the data, wrote the manuscript and approved the final version.

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