Korean J. of Chem. Eng., 8(3), 131-136 (1991)

PARTICLE VELOCITY AND CIRCULATION RATE IN LIQUID SPOUTED BEDS

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(Received 11 August 1990 • accepted 5 June 1991)

Abstract—In this work, the particle velocity and circulation rate in water spouted beds of small glass particles are experimentally studied. The pathline, velocity and residence time of particles 0.53 to 1.40 mm in diameters were measured in the annulus of half-cylindrical columns 40, 60 and 90 mm in diameters. The particle velocity in the annulus and circulation rate increase practically linearly with fluid flowrate. As the column diameter was increased, the average particle velocity in the annulus was decreased, but the particle circulation rate was increased.

INTRODUCTION

The characteristics of the fluid and particle movements in a spouted bed are important for the applications of spouted beds in drying, particle coating, granulation and thermal cracking, etc. [1]. There are two kinds of approaches in the literature for predicting the particle circulation rate in a spouted bed [1]. Thorley et al. [2] calculated the particle velocity profile in the spout from a force balance for a particle, while Lefroy and Davidson [3] calculated the axial voidage and particle velocity profiles in the spout solving momentum balance equations.

Recently, Morgan et al. [4] applied the mass and momentum balance approach with a derived expression for the interaction force between the fluid and particle phases and calculated the particle velocity in the spout and circulation rate. They showed that their theory could predict the particle velocity in the spout for the coarse particle-air system by taking into account the spout diameter variation near the jet inlet [5]. In order to predict the particle velocity accurately with this method, the spout diameter variation should be taken into account since a slight variation in diameter causes great effect on the fluid and particle velocities there [5]. This effect is greater for the liquid spouting since the spout diameter variation in liquid spouted beds is greater than that of gas spouted beds [6].

In this work, the particle pathline and velocity of small glass particles, 0.53 to 1.40 mm in diameters, were measured in the flat face of the half-cylindrical columns of 40, 60 and 90 mm in diameters in order to explore the flow characteristics of small particles in liquid spouted beds. In addition, the effects of spout inlet fluid flowrate above minimum and column diameter on the particle flow are also investigated.

EXPERIMENTAL

The experiments were carried out in the apparatus shown in Fig. 1. The spouted bed in the figure is a cylindrical half-column 40, 60 and 90 mm in diameters and 800 mm high. Each column has a spout inlet whose diameter is 4.2, 8.0 and 12.2 mm, respectively. The bed is made of transparent acrylic resin and has a flat base. There is a pressure tap at the spout inlet to measure the bed pressure drop and it is connected to the piezometer tube. The water was filtered and the temperature was kept at 25± 0.5℃.

The pressure drop in the bed, annulus height and jet height are measured with decreasing fluid flowrates. The criterion for determining H_m and $(U_{ms})_{Hm}$ was formulated by observing the change in the shape of the jet with decreasing fluid flowrates. $(U_{ms})_{Hm}$ is the highest fluid velocity for which the flame tip jet is visible and is slightly higher than U_{mf}(Table 1). H_m is the height from the spout inlet to the tip of the flame shape jet at $(U_{ms})_{Hm}$. Other details of the experimental equipment and procedure can be found in Kim and Ha [7].

The particle pathline and velocity in the annulus

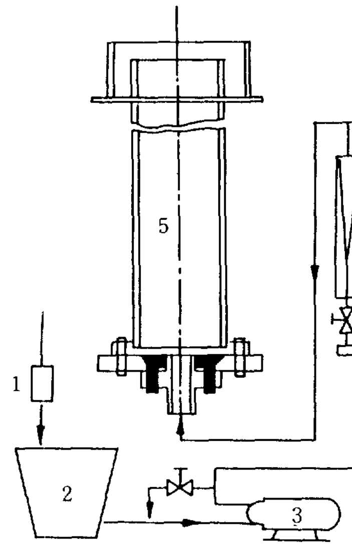

Fig. 1. Schematic diagram of experimental apparatus; 1. water filter, 2. water tank, 3. pump, 4. rotameter, 5. spouted bed.

Table 1. Experimentally measured spouted bed properties in the condition of minimum spouting, $D_c=40$ mm, $d_i=4.8$ mm

d_p (mm)	ρ_p (kg/m^3)	U_{mf} (mm/s)	ε_{mf}	H (mm)	h	U_{ms} (mm/s)	d_s (mm)
0.53	2440	3.15	0.400	58.5	0.8	3.59	9.9
				73.1	1	3.87	12.2
0.77	2500	5.36	0.400	52.7	0.8	6.22	12.0
				65.9	1	6.81	13.0
1.10	2490	7.64	0.403	44.8	0.8	8.94	12.2
				56.0	1	9.55	13.2
1.40	2910	17.46	0.406	40.1	0.8	18.27	12.7
				50.1	1	20.95	14.3

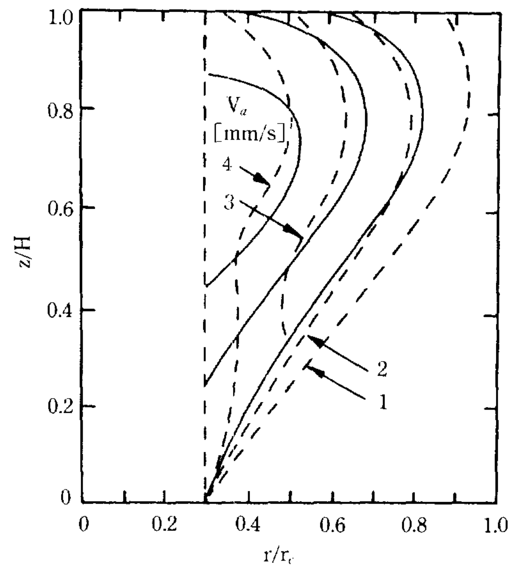

Fig. 2. Pathlines(—) and equi-velocity lines(---) of the particles in the annulus; $D_c=40$ mm, $d_p=0.77$ mm, $H=0.8H_m$, $U=1.25U_{ms}$.

were first measured by visual observation through the transparent flat wall of the half-column since the particle velocity was less than 4 mm/s except for the region close to the spout. The experiment was videotaped (Camera: DXC-1640, VTR U-Matic 3/4 VO-2860, Ed. Unit: RM-430) and the pathlines and velocity of the particles were analyzed. Agreement between the two measurements was very good. The particle velocity in the spout was obtained from the analysis of high speed pictures of 300 fps with a motion analyser (NAC High Speed Camera: Model E-10, 16 mm, Motion Analyser: 160F).

RESULTS AND DISCUSSION

Typical particle pathlines and equi-velocity lines for 0.77 mm particles are shown in Fig. 2. The column is 40 mm in diameter, bed height is 0.8 H_m and fluid velocity is 1.25 U_{ms}. At $U=U_{ms}$ and $H=H_m$, particles enter the annulus in the top half of the bed where the spout diameter expands and reenter the spout near the spout inlet. As the flowrate is increased above U_{ms} and bed height is shallower than H_m, the spout diameter is more uniform and more particles enter the annulus near the top of the bed compared with that at U_{ms} and H_m. Particle velocity distribution in the annulus is also shown in Fig. 2. As can be seen in the figure, the particles near the spout move faster than those near the column wall. The residence time distribution of the particles in the annulus is broad and the particle entering the top of the annulus near the wall has a longer residence time. The particles moving along the pathline near the wall have longer residence time since they move slower and have longer pathlines compared to the particles moving near the spout. And the particle residence time in the annulus at the minimum spouting was approximately three times that of fluid which has a similar streamline to the particle pathline but the difference is getting smaller as the spout inlet fluid flowrate is increased above the minimum. For the air-coarse particle system of Day et al. [5], one can find the average particle residence time is approximately 30 times that of fluid.

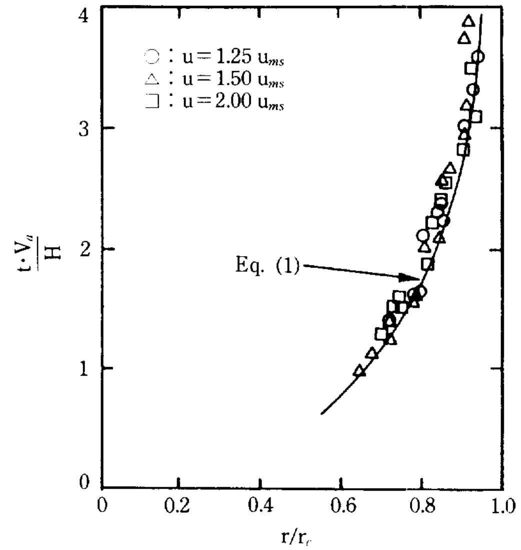

Fig. 3. Normalized particle residence time distribution along a pathline in the annulus as a function of radial position at the top of the bed; D_c=40 mm, d_p=0.77 mm, H=0.8H_m.

Although the fluid residence time in the annulus is clearly related to the particle residence time there, and the ratio between the residence time of particle and that of fluid is different for gas and liquid spouting, it is difficult to show theoretically why the particle residence time measured in this study is approximately 3 times that of fluid since no theoretical model exists for the particle velocity distribution in the annulus. In spouted beds, the fluid flow model was developed in the annulus, and the material balance of the fluid is applied to obtain the average fluid velocity in the spout. On the other hand, the particle flow model was developed in the spout and the average particle velocity in the annulus was calculated from the material balance of the particles.

The measured residence time of 0.77 mm particles in the annulus at H=0.8 H_m, normalized by U/H, are shown in Fig. 3 for the spout inlet flowrates of 1.25, 1.50 and 2.00 U_{ms}. The normalized residence time distribution practically follows a single curve for the fluid flowrate studied. Least square fitting of the data gives

$$\frac{tU}{H} = 16.1 - 45.4(r/r_c) + 34.5(r/r_c)^2 \qquad (1)$$

with correlation coefficient of 0.975.

The data of 0.53, 1.10 and 1.40 mm particles show the same behavior. Since H is practically constant for the fluid flowrate varied, t is inversely proportional to U. Consequently, this suggests that the particle velocity in the annulus is proportional to U. In order to delineate this effect, the average particle velocity in the annulus was measured along the particle pathline which starts at the top of the annulus near r/r_c= 0.5. As expected, V_a increased linearly with normalized fluid velocity, U/U_{ms}, and the slope of the line increased with particle size.

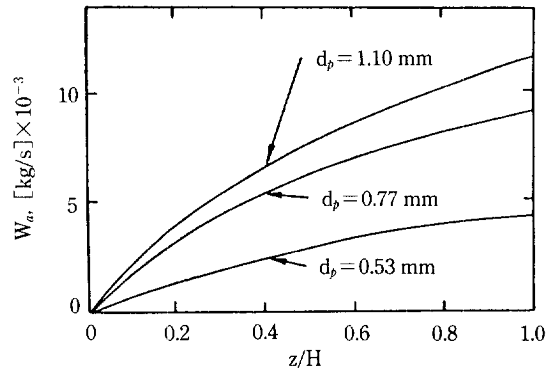

Fig. 4. Particle circulation rate calculated from Eq. (2); D_c=40 mm, H=0.8H_m, U=1.25U_{ms}.

The particle circulation rate was calculated from Eq. (2).

$$W_a = \rho_p A_a (1-\varepsilon_a) V_a \qquad (2)$$

In calculating W_a from Eq. (2), ε_a was assumed to be equal to ε_{mf} which was measured and the measured values of V_a were used. As shown in Fig. 4, the particle circulation rate increases with bed height and particle size at a given value of z/H. This behavior is similar to that of air spouted beds of coarse particles [4, 5].

The effect of fluid flowrate above minimum on the particle flowrate is shown in Fig. 5. The figure shows that W_a increases with U/U_{ms} for all values of z/H. Since the average particle velocity increases linearly with fluid flowrate and $\rho_p A_a(1-\varepsilon_a)$ in Eq. (2) is practically constant for the flowrate studied, the particle circulation rate also increases linearly with U/U_{ms}. For gas spouted beds of quartz, coal and mustard seed of 1.08-2.48 mm in diameter, Van Velzen et al. [8] also reported the solid circulation rate is proportional to fluid flowrate.

The particle velocity and pathline were also measured in larger columns, 60 and 90 mm in diameters. The contour maps of the particle pathlines and equivelocity lines in these beds are similar in shape to that of 40 mm column. The average particle velocity measured near the top of the annulus for the different columns are shown in Table 2. The table shows that

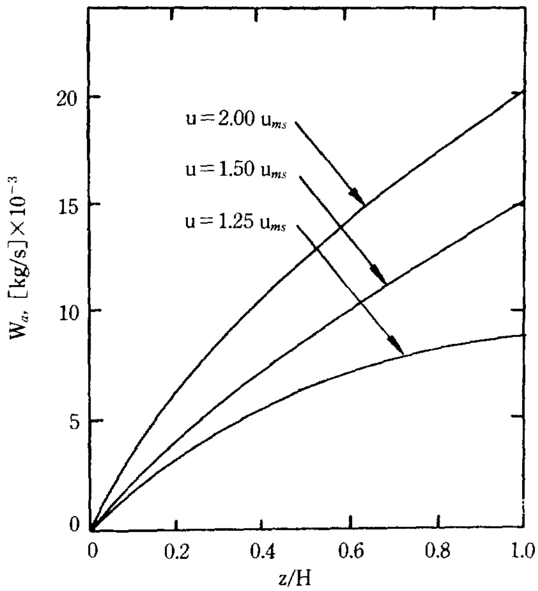

Fig. 5. Effect of spout inlet fluid flowrate on the particle circulation rate; D_c=40 mm, d_p=0.77 mm, H=0.8 H_m.

Table 2. Experimentally measured spouted bed properties, d_p=0.77 mm, H=0.8H_m, U=1.25U_{ms}, ε_a=0.400

D_c (mm)	40	60	90
d_i (mm)	4.2	8.0	12.2
H (mm)	52.7	68.0	90.4
d_s (mm)	12.0	12.8	14.0
V_a (mm/s)	3.4	2.0	1.2
W_a (kg/s)	0.0056	0.0099	0.0136

the average particle velocity in the annulus decrease rapidly with increasing column diameter and the effect of the column size can be expressed as $(D_c/40)^{-1.25}$. However, the particle circulation rate increased with column diameter for the same value of U/U_{ms}.

The spout particle velocity distributions of 0.77 mm particles for different fluid flowrate in 60 mm column are obtained from the analysis of high speed film. Fig. 6 shows that the particles are accelerated rapidly near the spout inlet to a maximum which is much greater than U_t, 123 mm/s, at z/H around 0.3, then decelerated as they approach the top of the spout. The particle velocity increased with spout inlet fluid flowrate everywhere in the spout. It is observed that the spout diameter is practically constant in the region where the particles are accelerated while the diameter expands in the decelerating zone.

$$W_s = \rho_p A_s(1-\varepsilon_s)V_s \tag{3}$$

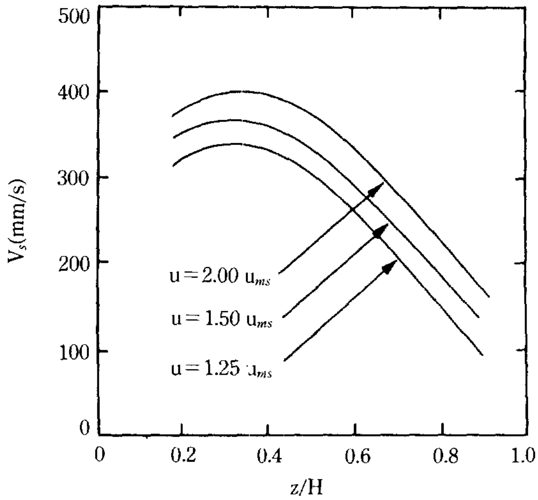

Fig. 6. Particle velocity distribution measured in the spout; D_c=60 mm, d_p=0.77 mm, H=0.8H_m.

Particle circulation rate was also calculated from Eq. (3) using the measured particle velocity in the spout. At U=1.25 U_{ms}=78 mm/s, H=0.8 H_m=68 mm and D_c=60 mm, W_s is 8.75 g/s. In the calculation of W_s, d_s was assumed to be constant and ε_s was taken from Lefroy and Davidson theory based on Ergun friction factor (4). W_a calculated from Eq. (2) using the measured V_a is 8.1 g/s which is slightly lower than W_s.

Although the two approaches [2, 4] for predicting W_s are similar in concept, the final equations for W_s are very different. Thorley et al. [2] derived Eq. (4) for the particle circulation rate.

$$W_s = \rho_p A_s[1-\varepsilon_s(H)][2g(\rho_p-\rho_f)(H'-H)/\rho_p]^{1/2} \tag{4}$$

In the equation, H' and H are the heights of the spout fountain and annulus, respectively. Morgan et al. [4] derived Eq. (5) for W_s.

$$W_s = \rho_p A_s(gH)^{1/2}\{[1-\varepsilon_s(H)]\frac{\rho_p-\rho_f}{\rho_p}C_o[\varepsilon_s(H)-\varepsilon_{mf}] - [1-\varepsilon_s(H)]\frac{\rho_f}{\rho_p}\frac{\varepsilon_s(H)[U_s(H)]^2-\varepsilon_{mf}[U_s(H)]^2_{ms}}{gH}\}^{1/2} \tag{5}$$

where $C_o = \Delta P_{ms}/\Delta P_{mf} + \dfrac{\rho_f\{[U_s(O)]^2_{ms}-\varepsilon_{mf}[U_s(H)]^2_{ms}\}}{(1-\varepsilon_{mf})(\rho_p-\rho_f)gH}$

based on the momentum balance approach of Lefroy and Davidson[3]. For the spouting of small particles with liquid at or near the minimum spouting condition, the inertial force of the jet is less than 10% of the bed pressure drop, so that Eq. (5) can be reduced to Eq. (6).

$$W_s=\rho_p A_s \{[1-\varepsilon_s(H)][\varepsilon_s(H)-\varepsilon_{mf}][1-\frac{\rho_f}{\rho_p}][\frac{\Delta P_{ms}}{\Delta P_{mf}}]gH\}^{1/2} \quad (6)$$

Eqs. (4) and (6) were used to calculate W_s. In the calculation, the measured values of H=68 mm, H'=69 mm, $\Delta P_{ms}/\Delta P_{mf}=0.50$ and $d_s=12.8$ mm were used. W_s calculated from Eq. (4) is 13.9 g/s, and that calculated from Eq. (6) is 7.6 g/s. Agreements between the values for W_s obtained from this study and calculated from Eq. (6) are good. However, Eq. (4) predicts W_s which is substantially higher than that from Eq. (6) or of this study. In applying Eqs. (4) and (6), one has to know H' and $\varepsilon_s(H)$ accurately. Because H' is slightly higher than H and $\varepsilon_s(H)$ is slightly greater than ε_{mf}, a small change in these values will cause great effect on W_s.

The calculated values of particle circulation rate will be affected by the spout diameter variation. In liquid spouting of small particles, the spout-annulus interface is not clear in terms of voidage and the spout diameter expands in the region where the particles decelerate. Recently, Benkrid and Caram [9] reported that the particle velocity in the annulus of a gas spouted bed measured at the flat wall of the half-cylindrical column was substantially lower than that in the full column. This wall effect in the annulus as well as in the spout along with the spout diameter variation and spout voidage profile need further investigation.

CONCLUSIONS

The particle velocity in the annulus and the circulation rate increase practically linearly with spout inlet fluid flowrate.

As the column diameter is increased, the average particle velocity in the annulus is decreased, but the particle circulation rate is increased.

The particle residence time distribution in the annulus is broad and the particle residence time is approximately three times than that of fluid which has a similar streamline to the particle pathline at the minimum spouting, but the difference is getting smaller as the spout inlet fluid velocity is increased above the minimum.

The particle velocity increases with spout inlet fluid velocity everywhere in the spout and the paricle circulation rate calculated from the measured spout velocity is slightly higher than that in the annulus.

ACKNOWLEDGEMENT

The author wish to acknowledge a grant-in-aid for research from the KOSEF(Grant No.: 901-1001-018-2).

NOMENCLATURE

A_a : $(\pi/4)(D_c^2-d_s^2)$ [mm^2]
A_s : $(\pi/4)\ d_s^2$ [mm^2]
D_c : column diameter [mm]
d_i : spout inlet diameter [mm]
d_p : particle diameter [mm]
d_s : spout diameter [mm]
g : gravitational acceleration [m/s^2]
H : height of the annulus [mm]
H_m : maximum spoutable height in the condition of minimum spouting [mm]
H' : height of the annulus [mm]
h : H/H_m [−]
ΔP_{ms} : overall pressure drop at the minimum spouting in a bed of height, H [Pa/m^2]
ΔP_{mf} : minimum fluidization pressure drop in a bed of height, H [Pa/m^2]
r : distance from the axis of symmetry of the column [mm]
r_c : column radius [mm]
t : residence time of a particle along a pathline [mm/s]
U : superficial fluid velocity in the bed [mm/s]
U_{mf} : minimum fluidization velocity (superficial) [mm/s]
U_{ms} : minimum spouting velocity (superficial) [mm/s]
U_t : terminal fall velocity of a particle [mm/s]
V_a : particle velocity in the annulus [mm/s]
V_s : particle velocity in the spout [mm/s]
W_a : $\rho_p A_a V_a\ (1-\varepsilon_a)$ [kg/s]
W_s : $\rho_p A_s V_s\ (1-\varepsilon_s)$ [kg/s]
Z : vertical height from the spout inlet [mm]
ε_a : voidage in the annulus [−]
ε_{mf} : bed voidage in the minimum fluidization condition [−]
ε_s : voidage in the spout [−]
ρ_f : fluid density [kg/m^3]
ρ_p : particle density [kg/m^3]

Subscript

ms : in the condition of the minimum spouting

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