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FLUID AND PARTICLE FLOW CHARACTERISTICS IN A DRAFT TUBE SPOUTED BED WITH MODIFIED FLUID OUTLET

Seung Jai KIM

Department of Chemical Engineering, Chonnam National University, Yongbong-dong, Buk-ku, Kwangju 500-757, Korea

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Abstract—Glass particles, 0.54-1.39 mm in diameter, are spouted with air in a half-cylindrical draft tube spouted bed with modified fluid outlet to investigate the flow characteristics of the fluid and particles in the annulus. Using the measured pressure distribution and particle velocity and pathline in the annulus, the fluid streamlines, fluid and particle residence time distributions are obtained. Effects of the spout inlet fluid flowrate, distance between the draft tube and spout inlet and the modified fluid outlet on the flow fields are also discussed.

INTRODUCTION

Spouting is a technique for bringing a fluid into contact with solid particles in which the fluid is introduced vertically as a jet into a bed of particles, generally of millimeter size. Specific applications of the spouted bed technology are discussed by Mathur and Epstein [1].

The spouted bed are commonly regarded as being useful only for processes involving coarse particles. However, Hattori and co-workers [2-4] have spouted particles as small as those used in fluidized beds (as low as 0.27mm) in a bed equipped with an inner draft tube. In addition, they were able to eliminate all bypassing of the fluid entering the bed using the side outlet spouted beds. Because of their unique characteristics, the draft tube spouted beds (DTSB) or DTSB with side outlet have the potential for application in systems reserved for fluidized beds.

Experimental studies have been reported for particle path and gas distribution in the annulus of a porous DTSB [5], gas distribution and heat transfer [6] and drying characteristics [7] in draft tube spouted beds.

In this work, the fluid and particle flow characteristics in the annulus of DTSB and DTSB with modified fluid outlet were experimentally studied. The air at room temperature and spherical glass particles of 0.54 to 1.39 mm were used. Assuming the Ergun equation governing the flow field in the annulus and using the measured pressure distribution and voidage there, the fluid streamline, velocity and residence time were calculated. In addition, the effects of parameters such as spout inlet fluid flowrate, distance between the draft tube and the spout inlet, particle diameter and existence of the upper column are also discussed.

EXPERIMENTAL

The spouted bed used is given in Figure 1. The lower column is a half-cylindrical one of 128mm in diameter and of 400mm high. It is made of acrylic resin, has a flat base and is designed in such a way that a semicircular draft tube can be attached to the flat face of the lower column and moved vertically. The upper column, 80.5mm in diameter and 132mm high, can be attached and moved vertically, also. The flat and round faces of the column have 106 pressure taps which are connected to air-water U-tube manometers or inclined manometers. In the flat face of the half-cylindrical column, a rectangular grid of 91 pressure taps are distributed. The distance between the taps is shorter in the region near the spout inlet and the top of the annulus.

The flow and particle properties used in this study are shown in Table 1. The glass particles are spherical and air at room temperature was used for the experiment. U_{mf} was measured in a cylindrical fluidized bed 80mm in diameter and U_{ms} was also measured experimentally.

The variations of annulus heights and bed pressure drop between the spout inlet and the top of the draft tube are shown in Figure 2 as a function of spout inlet

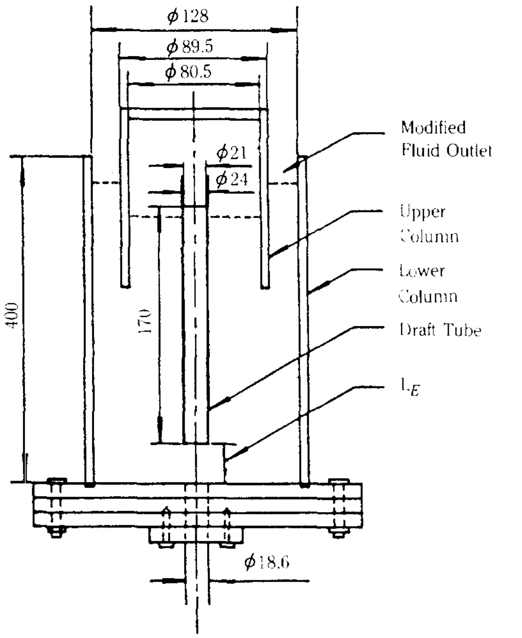

Fig. 1. Draft tube spouted bed with modified gas outlet (half-cylindrical); unit: mm.

Table 1. Flow and particle properties used: L_E = 22.5 mm, H_o = 180mm

d_p (mm)	ρ_p (kg/m^3)	U_{mf} (m/s)	ε_a	U_{ms} (m/s)
0.54	2460	0.21	0.410	0.137
0.85	2400	0.42	0.411	0.218
1.39	2840	0.83	0.432	0.429

fluid flowrate for 1.39mm particles. Before injecting the air, a known amount of particles are filled into the annulus, the space between the column wall and draft tube. The height of the packed annulus is slightly lower than that of the draft tube. Some particles moved from the annulus into the draft tube through the small space between the spout inlet and the bottom of the draft tube.

With increasing spout inlet fluid flowrate, the bed pressure drop increases till point A′ is reached where the fluid from the spout inlet can not break through the layer of particles about 10mm thick which moved into the draft tube when the particles were filled into the bed. As the spout inlet flowrate is increased slightly above A′, the jet breaks the particle layer and the particles spread over the most of the draft tube, but do

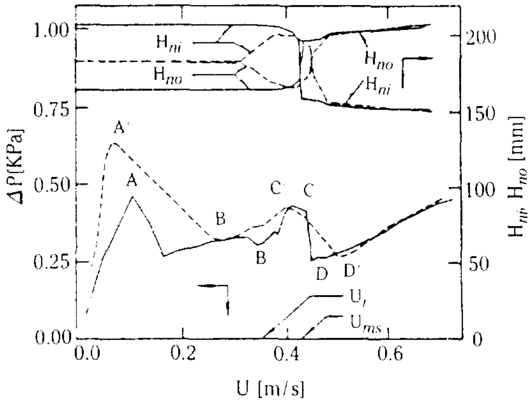

Fig. 2. Pressure drop and annulus heights as a function of flowrate; d_p = 1.39mm, L_E = 22.5mm, H_o = 180mm, —: decreasing flowrate, -----: increasing flowrate.

not flow out of the draft tube. When the flowrate is above point B′, the particle are transported out of the draft tube, however, the process is unstable until point C′ is reached. Between C′ and D′, the spouting as well as the particle transport is steady. As the flowrate is increased above D′, bubbles or jets form in the annulus between the lower and the upper column since the fluid velocity there at this flowrate is above U_{mf}.

At the beginning of the experiment, the height of the inner annulus, H_{ni}, between the draft tube and the upper column is approximately same as that of outer annulus, H_{no}, between the upper and the lower column. The height of the annulus does not change up to B′, then H_{ni} increases until C′ is reached and decreases as the flowrate is increases further. When the spout inlet flowrate is above point D′ or D, H_{ni} becomes lower than H_{no} as can be seen in Figure 2, however, when the fluid flow is stopped H_{ni} is higher than H_{no}.

The fluid velocity for the incipient spouting (U_i), the minimum fluid velocity for stable spouting (U_{ms}) and the maximum fluid velocity for stable spouting (U_m) without bubbles or jets in the outer annulus are determined from decreasing flowrate in Figure 2. A, B, C and D in decreasing flowrate represent the same characteristics as A′, B′, C′ and D′ in increasing flowrate. In the figure U_i corresponds to the fluid velocity at point B, U_{ms} at point C and U_m at point D. U_i, U_{ms} and U_m are given as a function of fluid-particle system, bed geometry and parameters such as the distance between the spout inlet and the draft tube (L_E) and the height of the annulus.

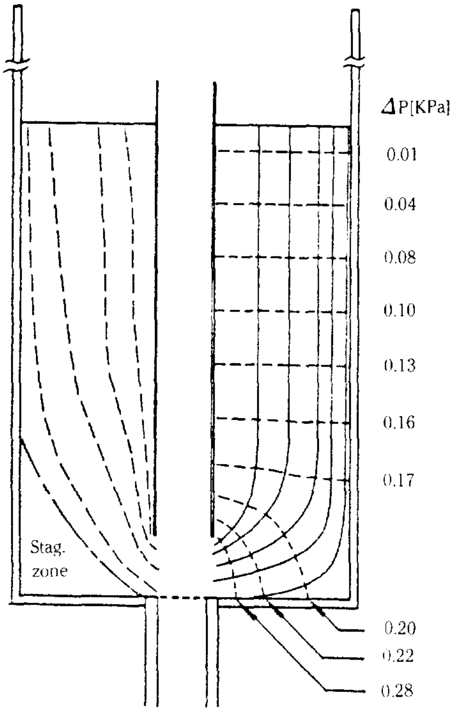

Fig. 3. Pressure distribution (-----), fluid streamlines (—) and particle pathlines (---) in the annulus of a draft tube spouted bed; d_p = 1.39mm, $U = U_{ms}$ = 0.429 m/s, L_E = 22.5mm, H_o = 180mm.

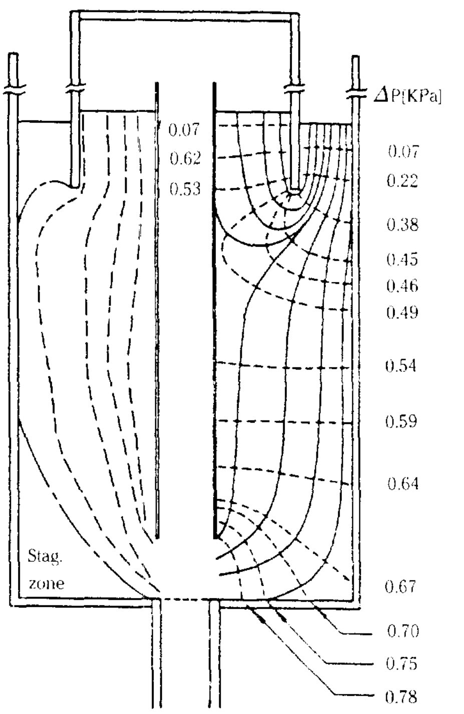

Fig. 4. Pressure distribution (-----), fluid streamlines (—) and particle pathlines (---) in the annulus of a draft tube spouted bed with modified fluid outlet; d_p = 1.39mm, $U = U_{ms}$ = 0.429 m/s, L_E = 22.5mm, H_o = 180mm.

RESULTS AND DISCUSSION

The measured fluid pressure distribution and particle pathlines, and calculated fluid streamlines in the annulus of a draft tube spouted bed are shown in Figure 3 for 1.39 mm particles. In the calculation of fluid streamlines and velocity, the Ergun equation was used along with the measured pressure distribution and voidage shown in Table 1. The wall effects, no slip boundary condition and high voidage near the wall, are neglected in this study. Similar plots for 1.39mm particles with modified fluid outlet are shown in Figure 4.

The radial pressure in the annulus of the DTSB, Figure 3, does not vary greatly and the gas streamlines show that the fluid flow is practically plug flow except for the region close to the spout inlet. These are similar to those reported earlier [2-4,8].

In order to eliminate the gas bypass completely, the gas outlet was modified by attaching a half-cylindrical upper column coaxially. As can be seen in Figure 4, the pressure and flow fields in a DTSB with the modified fluid outlet are greatly affected by the modified fluid outlet. The fluid streamlines shown in Figure 3 and Figure 4 are drawn normal to the isobars.

When the spout inlet fluid flowrate was varied, the manometer readings became constant in several seconds and one can observe steady movement of the particles in the bed. However, once bubbles or jets form in the modified fluid outlet, the flow as well as pressure fields become unsteady.

The fluid residence time calculated from the Ergun equation along the various streamlines as a function of radial location at the top of the annulus is shown in Figure 5. As expected, the residence time distribution of fluid in the annulus of a DTSB is narrower than that of conventional spouted beds [9]. In a modified gas outlet DTSB, the fluid from the inlet is divided into two, i.e. one through the annulus only and the other through the draft tube and the annulus. The fluid residence time distribution for the latter is broader than the former. The residence time of the fluid through the annulus only was longer than that through the draft tube and the annulus in this study because the dis-

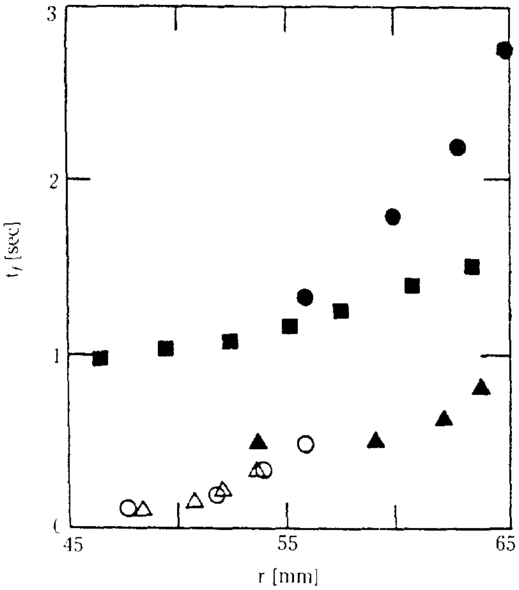

Fig. 5. Fluid residence time distribution as a function of radial location at the top of the annulus; U = U_{ms}, L_E = 22.5mm, H_o = 180mm; ○, ●: d_p = 0.85mm; △, ▲, ■: d_p = 1.39mm; unfilled circle or triangle represent flow through the draft tube; ■ : without upper column.

tance between the jet inlet and the bottom of the upper column is much greater than that between the bottom of the upper column and the top of the inner annulus.

Since it was difficult to measure the particle movement near the top of the annulus, the residence time in the annulus was measured along the particle pathline beginning just below the bottom of the upper column, and the results are shown in Figure 6 as a function of radial location just below the bottom of the upper column. The particle pathline and velocity were measured by visual observation using a stop watch through the transparent flat face of the half-cylindrical column. For this experiment, another DTSB which is the same as the one in Figure 1 but without pressure taps in the annulus, was used. A transparent paper with horizontal and vertical lines of 5mm in distance was attached on the flat face.

As shown in Figure 6, the particles moving closer to the draft tube have somewhat longer residence time than those slightly away from it and the particles moving close to the column wall have the longest residence time.

Effect of the spout inlet fluid flowrate above V_{ms} on the particle residence time is given in Figure 7. As expected, the particle residence time decreases with increasing the fluid flowrate since the particle

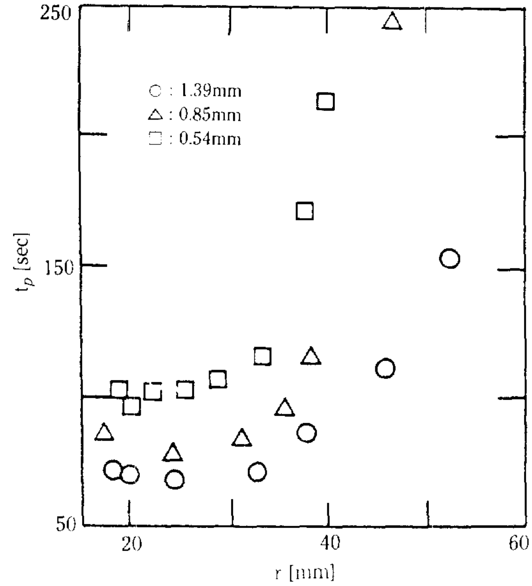

Fig. 6. Particle residence time distribution in the annulus as a function of radial location just below the bottom of the upper column; U = 1.25 U_{ms}, L_E = 22.5 mm, H_o = 180 mm.

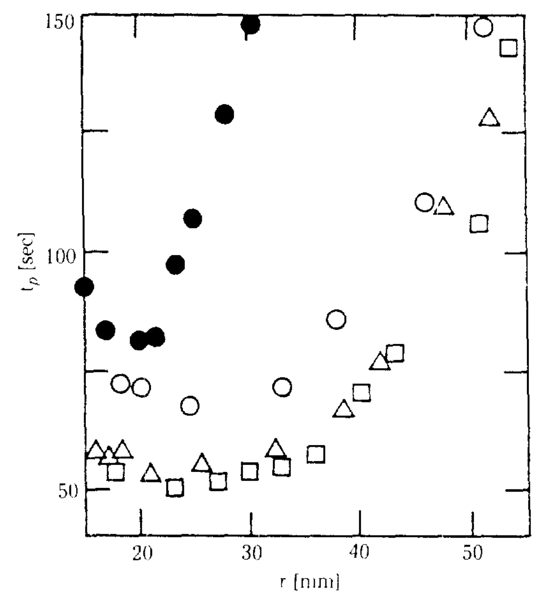

Fig. 7. Effect of spout inlet flowrate on the particle residence time; d_p = 1.39 mm, L_E = 22.5 mm, H_o = 180 mm; ● : U = U_{ms}, ○ : U = 1.25 U_{ms}, △: U = 1.50 U_{ms}, □ : U = 1.75 U_{ms}.

transport rate through the draft tube increases with spout in let fluid flowrate. Under the present experi-

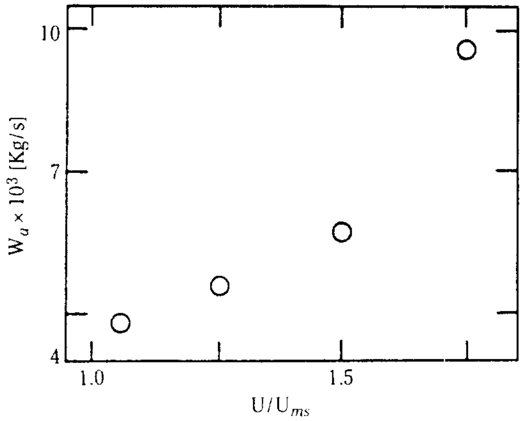

Fig. 8. Effect of spout inlet flowrate on the particle circulation rate in the annulus; d_p = 1.39 mm, L_E = 22.5 mm, H_o = 180 mm.

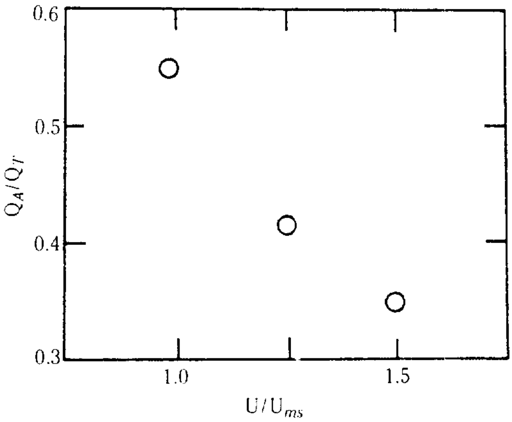

Fig. 9. Effect of spout inlet fluid flowrate on Q_A/Q_T; d_p = 1.39 mm, L_E = 22.5 mm, H_o = 180 mm.

mental conditions, the particle residence time decreases approximately linearly with increasing the fluid flowrate except for the region close to the column wall where the particles move slowly and their pathlines are long. The particle velocity measured in the flat face of the column was averaged and the particle circulation rate was calculated for the different spout inlet flowrates. Figure 8 shows that the particle circulation rate increases rapidly with the spout inlet fluid flowrate.

In order to study the effect of the spout inlet fluid flowrate on the flow through the annulus (Q_A) versus the total flow (Q_T), Q_A and Q_T were calculated from the Ergun equation and material balance. As can be seen in Figure 9, the Q_A/Q_T decreases rapidly with increasing spout inlet fluid flowrate. This behavior is similar

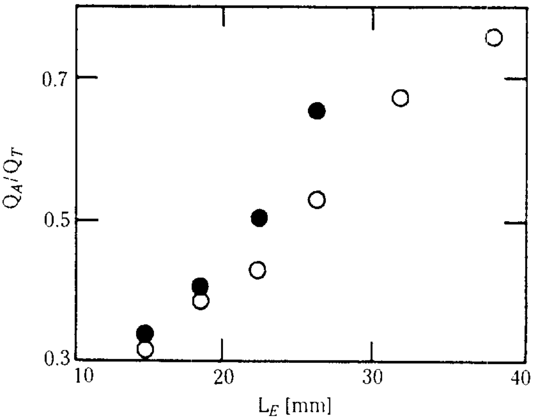

Fig. 10. Effect of L_E on Q_A/Q_T; d_p = 1.39 mm, U = 1.03 U_{ms}, H_o = 180 mm; unfilled circles represent the data with upper column.

to that of conventional spouted beds. As the spout inlet fluid flowrate is increased above V_{ms}, the height of the annulus between the draft tube and the upper column, H_{ni}, decreases. If H_{ni} decreases with increasing spout inlet fluid flowrate, the fluid flow through the draft tube has less resistance to flow so that more fluid can take this easy path. When the spout inlet flowrate is increased above 1.5 V_{ms}, the fluid velocity in the annulus between the lower and the upper columns becomes greater than the minimum fluidization velocity. In this case, bubbles or jets form there and the pressure and flow fields are unstable.

Figure 10 shows the effect of L_E on Q_A/Q_T. Q_A/Q_T increases with L_E in both beds, however, the higher value was obtained for a bed with the upper column where the pressure build-up inside the upper column forces more fluid flow through the annulus.

In order to examine the effects of L_E and Q_T on the spouting regime, L_E was first fixed at the minimum value of 15.0mm and the U_{ms} was measured. The values were 0.115, 0.171 and 0.287 m/s for 0.54, 0.85 and 1.39 mm particles, respectively. By increasing U and L_E, the spouting behavior was carefully observed, and the results are given in Figure 11. In the figure, the region under the solid line represents stable spouting region for each particle size. In the region between the solid and dotted lines, spouting occurs but unstable. Above the dotted line, spouting does not occur since the particles in the draft tube do not move.

The bed is designed in such a way that the cross sectional area between the draft tube and the upper column (A_{ni}) is approximately equal to that between the lower and the upper column (A_{no}). If one increases the value of A_{no}/A_{ni}, then A_{ni} decreases and

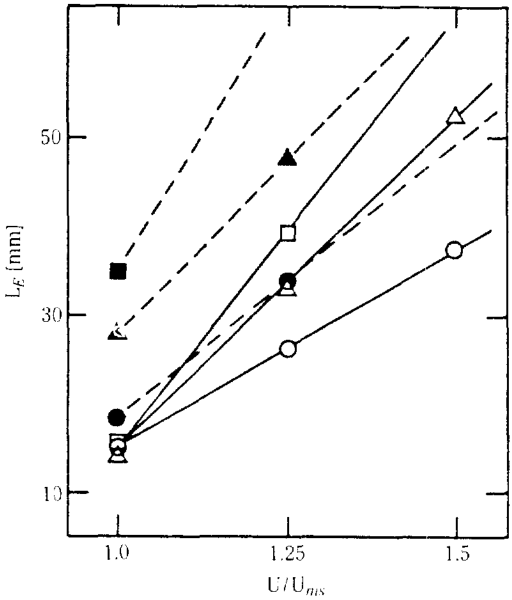

Fig. 11. Effects of L_E and Q_T on spouting regime; H_o= 180mm; □, ■ : d_p= 1.39mm; △, ▲: d_p= 0.85 mm, ○, ●: d_p = 0.54 mm; —: maximum L_E for stable spouting, -----: maximum L_E for incipient spouting.

H_{ni} decreases also since the particles there are pushed down more. This will cause decrease in the fluid-particle contact time for the fluid flowing through the draft tube. If A_{no} is decreased, on the contrary, bubbles or jets are formed in the annulus between the upper and lower columns since the fluid velocity there is increased and exceeds U_{mf} in most operations. One method of eliminating the unstability due to bubbles or jets in this region is to use two-stage spouted bed which has bigger column diameter in the top section of the lower column.

CONCLUSIONS

1. Fluid residence time distribution in a draft tube spouted bed with modified gas outlet is broader than that of a draft tube spouted bed.

2. Increasing the spout inlet fluid flowrate above the minimum spouting increases the particle circulation rate, but decreases the fluid residence time and Q_A/Q_T.

3. Incipient, minimum and maximum spouting velocities increased with draft tube spacing, L_E. The relationship between these velocities and L_E are given in Figure 11.

4. In designing the side outlet DTSB using the upper column, the diameter ratio of the upper to the lower column is critical. If the ratio is too small, the particles in the inner annulus are pushed down, otherwise bubbles or jets are formed in the outer annulus when the fluid velocity exceeds U_{mf} which makes the system unstable.

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NOMENCLATURE

A_c : cross sectional area of the lower column [m^2]
A_{ni} : cross sectional area between draft tube and upper column [m^2]
A_{no} : cross sectional area between upper and lower columns [m^2]
d_p : average particle diameter [mm]
H_{ni} : height of the annulus, A_{ni}, from the spout inlet [mm]
H_{no} : height of the annulus, A_{no}, from the spout inlet [mm]
H_o : initial height of the packed bed [mm]
L_E : vertical distance between spout inlet and draft tube [mm]
ΔP : pressure drop between the spout inlet and the top of the draft tube [kPa]
Q_A : volumetric flowrate of fluid through the annulus [m^3/s]
Q_T : total volumetric flowrate of fluid through the bed [m^3/s]
r : radial distance from the axis of symmetry [mm]
t_f : fluid residence time [s]
t_p : particle residence time [s]
U : superficial fluid velocity [m/s]
U_i : U at incipient spouting condition [m/s]
U_m : maximum value of U for stable spouting [m/s]
U_{mf} : minimum fluidization velocity [m/s]
U_{ms} : minimum value of U for stable spouting [m/s]
V_{ms} : $U_{ms} \times A_c$ [m^3/s]
W_a : particle circulation rate in the annulus [kg/s]

Greek Letters

ε_a : voidage in the annulus [-]
ε_{mf} : voidage in the minimum fluidization condition [-]
ρ_p : particle density [kg/m^3]

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