NOTE

Mixing Behaviour of Solids in Multiple Spouted Beds

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Stimulus response experiments are conducted in four different rectangular columns having two and three spout cells. A pink-coloured polymer material is used as bed material with ambient air as the spouting fluid. A pulse input of dark blue colour polymer material is used as the stimulus, when the column is operating under steady flow conditions, and the response measured. A mathematical model "plug flow–mixed flow in series" is used to fit the experimental data and the model parameters are evaluated.

Des expériences de réponse à des stimuli ont été menées dans quatre colonnes rectangulaires différentes ayant deux ou trois cellules de jaillissement. Un matériau polymère de couleur rose est employé comme matériau de lit avec l'air ambiant comme fluide de jaillissement. Une pulsation de matériau polymère de couleur bleu foncé est employée comme stimulus, quand la colonne fonctionne dans des conditions à l'état stable, et la réponse est mesurée. Un modèle mathématique (écoulement piston– coulement mixte en série) sert à caler les données expérimentales et les paramètres du modèle sont évalués.

Keywords: multiple spouted beds, solids mixing.

The spouted bed systems are efficient fluid–solid contacting devices, and find applications in particle drying and coating operations. In order to predict the performance of continuous spouted beds, a detailed knowledge of particle residence times in the bed becomes essential. Information concerning the gross mixing behaviour of solids can be obtained from either stimulus-response experiments or theoretical/semi-empirical models. A considerable amount of literature is available to understand the particle residence time distributions and solids mixing in single spouted beds (Mathur and Epstein, 1974). Based on the available information it may be concluded that the solids mixing in a single spout bed could be approximated to near perfect mixing.

In the case of multiple spouted beds, Foong et al. (1975) conducted some solids mixing experiments in a flat bottom column having seven spouts arranged such that one spout at the centre was completely surrounded by six, and having a triangular pitch of 150 mm. Wheat and millet were used as bed materials with air as the spouting fluid. The bed was operated close to minimum spouting condition. Based on their data, they concluded that the total bed volume comprised of 85.5% mixed flow region, 1.7% plug flow region and 12.8% dead water region.

The multispout systems reported by Murthy and Singh (1994) consisted of square spout cells arranged in a rectangular column having 2 or 3 cells in line, or 4 cells arranged in square pitch. The transitions found in the operation of these multiple spouted beds were represented by phase diagrams (Murthy and Singh, 1996) and the following were identified in these diagrams: static bed (region 1); partially spouted bed (region 2); stable spouting (region 3); spout oscillations and interference (region 4); and chaotic bed (region 5). When the bed was operated close to minimum spouting condition (region 3), the bed was stable with steady spouting; here, each spout cell could be treated as a single spout unit. However, as the fluid velocity was increased, the spout oscillations and interference of spout fountains increased (region 4), which in turn increased the solids transfer between the cells through the fountains in the upper regions of the cells; but, the solids recirculation in the lower portions of the bed remained unchanged.

It appears, therefore, that the solids mixing behaviour in the multiple spouted beds having geometry used by Murthy and Singh (1994) should depend on whether the bed was operated in region 3 or 4. The present study aims at understanding such a behaviour.

Experimental

The experiments were conducted in four rectangular columns having two and three spout cells; each spout cell was of square cross-section, and was provided with an inverted pyramid (apex angle 60°) at the bottom. The spout cell configurations are shown in Figure 1. The broader sides of the column were made of transparent perspex sheets for visual observations. The fluid inlet to each cell was a 12 mm diameter orifice. A polymer material (pink colour, d_p = 1.8 mm and l = 3.4 mm, cylindrical shape, bulk density = 556 kg/m^3) was used as the bed material and the same polymer material having dark blue colour was used as the tracer. Air at 32°C, and 101.3 kPa was the spouting fluid. Figure 2 shows a schematic line diagram of the experimental unit.

The column was filled with solids to the required bed height and the bed was brought into stable spouting condition by careful adjustment of air supply to individual cells. The solids inflow into the column was then started through a screw feeder, and the solids flow rate was adjusted to the required value. When the column operation attained steady state, a known quantity (weight as well as number of particles) of coloured polymer material (tracer) was directly added to the feed (pulse input) and simultaneously a stop

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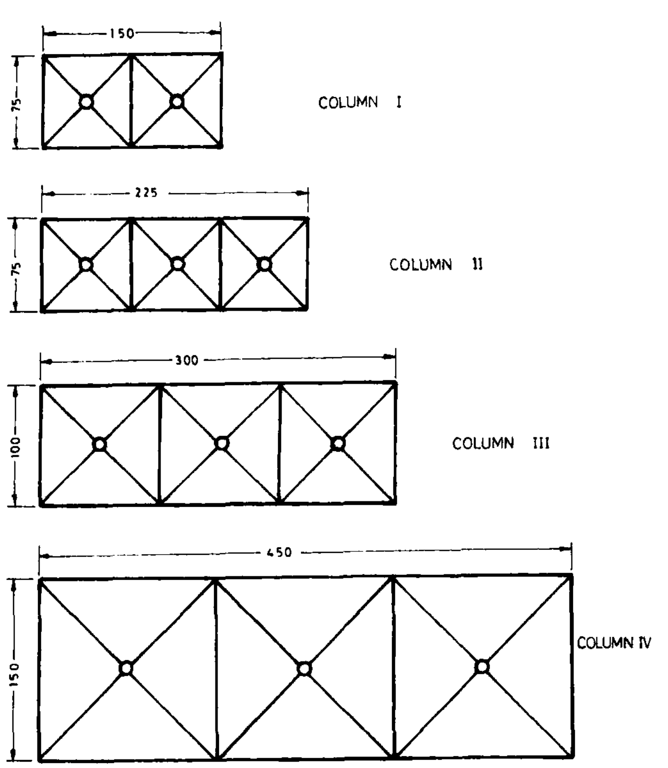

Figure 1. Spout column configurations.

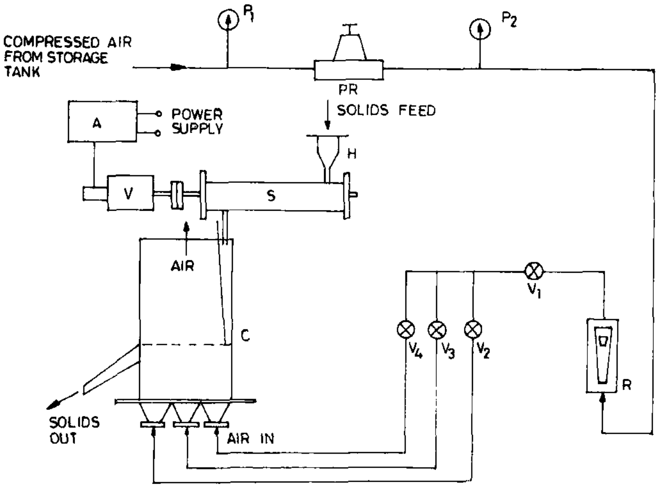

Figure 2. Schematic line diagram of experimental unit.
P_1, P_2 – Pressure gauges; PR – Constant Pressure Regulator;
R – Rotameter; V_1, V_2, V_3, V_4 – Globe Valves; C – Column;
H – Feed Hopper; S – Screw Feeder; V – Variable Speed Motor;
A – D.C. Control Panel.

watch was started. The samples at the outlet were collected at regular time intervals for over 2 to 5 mean residence times. The samples were analyzed for number of tracer and non-tracer particles. The response was expressed as fractions of tracer particles to total particles in the outlet at different times.

Column I (N = 2, a = 75 mm) and Column II (N = 3, a = 75 mm) had relatively fewer solids holdup and were operated at higher superficial air velocities, well above minimum spouting velocities; at these velocities spout oscillations and interference were observed. Column III (N = 3, a = 100 mm) was run at lower air velocities such that spout oscillations were very less. The air velocities in Column IV (N = 3, a = 150 mm) were maintained close to minimum spouting condition. Columns III and IV had relatively more solids holdup.

Results and Discussion

When the bed was operated in a continuous mode, the solids were fed at one end of the column into the annular region of a cell close to the wall and taken out from the annular region of the cell located at the opposite end of the column. Since each spout cell consisted of peripheral region, which could be treated as a slow downward moving packed bed, and a spout region with fast upward moving solids, the net flow of solids through the bed might be through a series of annulus-spout regions. Also, there might be a certain solids crossflow between the spout and the annulus regions.

In order to understand the gross mixing behaviour of solids, the bed as a whole might be considered to consist of plug flow and mixed flow regions operating in series. Since the spout cells were provided with inverted pyramids at their bottoms, it was expected that there would be no dead zones in the bed. Accordingly, the following mathematical model, "plug flow–mixed flow in series" (Fogler, 1992), was used to fit the experimental data:

$$I(\theta) = \exp\,[-v/v_m\,(\theta - v_p/v)] \qquad (1)$$

The model parameters, v_p/v and v_m/v, were evaluated using MATLAB software package. The experimental conditions and model parameters are given in Table 1.

The results indicated that when the solids holdup was relatively small and the superficial air velocities were relatively high (as maintained in Columns I and II), the fraction of mixed flow volume was higher. The presence of spout oscillations and interference of spouts in the two columns enhanced the solids transfer between the cells. So, the bed as a whole behaved more like a mixed flow system with a certain fraction of plug flow region. It was seen that higher mixed flow fractional volumes were obtained in these two columns.

A relatively larger solids holdup and lower superficial air velocities (as maintained in Columns III and IV) lowered the spout oscillations considerably; this in turn decreased the solids transfer between the cells through the fountains. The bed as a whole appeared as if a number of independent single spout cells were operating in series. Since each single spout cell may be treated as almost a perfect mixer, the solids mixing behaviour of multispout bed as a whole might tend towards plug flow. This may be inferred by higher plug flow fractional volumes obtained in columns III & IV.

A performance comparison between Columns II, III and IV having three spout cells revealed that as the solids holdup increased and air velocity decreased, the fraction of plug flow region increased.

The plots of $I(\theta)$ vs. θ for the columns used in the study are shown in Figure 3 indicate that the PF–MF in series model fitted the experimental data well.

Spout Mixing Number

In the operation of a continuous multispout system, solids flow rate and fluid superficial velocity play an important role to achieve steady spouting conditions. In order to understand the importance of these two operating parameters used in this study the following dimensionless group, called the *spout*

Table 1. Experimental parameters and model parameters.

Sl. No.	a mm	H cm	W kg	F_s g/s	Q m^3/s	V_0 m/s	t_m s	v_p/v	v_m/v	α
					I. NUMBER OF CELLS = 2					
1	75	8	0.6334	28.0	0.0057	0.5037	23.82	0.286	0.714	120
2	75	11	0.8211	26.9	0.0060	0.5333	33.09	0.314	0.686	182
3	75	18	1.2589	45.1	0.0070	0.6222	28.70	0.302	0.698	207
					II. NUMBER OF CELLS = 3					
4	75	5	0.7491	26.3	0.0075	0.4440	35.14	0.350	0.650	106
5	75	8	1.0306	22.0	0.0081	0.4800	51.99	0.147	0.853	218
6	75	10	1.2182	31.5	0.0086	0.5096	35.73	0.199	0.801	202
					III. NUMBER OF CELLS = 3					
7	100	10	2.2000	61.5	0.0117	0.3886	33.31	0.371	0.629	105
8	100	12	2.6216	65.3	0.0123	0.4110	38.89	0.363	0.637	126
9	100	14	2.9552	75.3	0.0133	0.4440	28.31	0.390	0.610	138
					IV. NUMBER OF CELLS = 3					
10	150	5	4.0715	69.8	0.0123	0.1826	54.85	0.431	0.569	33
11	150	7	4.8221	81.5	0.0145	0.2148	54.35	0.524	0.476	46
12	150	9	5.5727	84.0	0.0152	0.2240	63.17	0.435	0.565	60

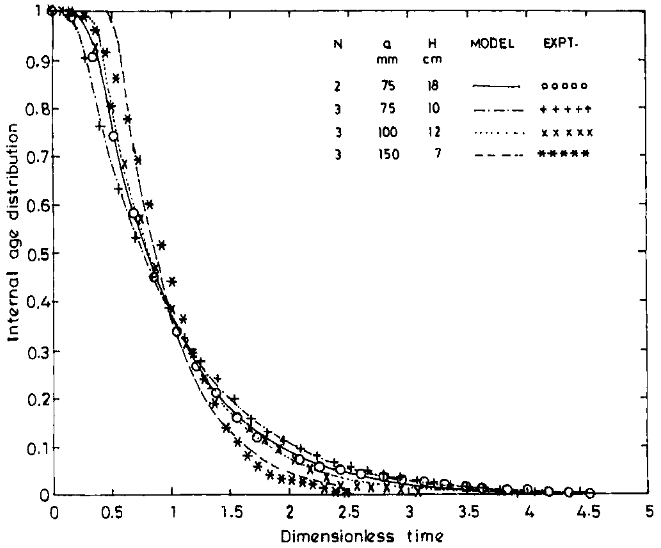

Figure 3. Internal age distribution vs. dimensionless time.

mixing number, α has been proposed:

$$\alpha = (N\, a\, H\, U_0)/(F_s/\rho_b) \tag{2}$$

The physical significance of this group may be explained as follows:

- When solids flow rate, F_s is low, and fluid superficial velocity, U_0 is high, α becomes large. Under these conditions the spout oscillations increase (close to region 4, or in region 4 itself), resulting in solids transfer between the cells. So, the fraction of mixed flow volume in the bed as a whole increases.
- When F_s is high and U_0 is low, α becomes small. Under these conditions the bed is likely to be operating in region 3, resulting in lower mixed flow volume in the bed.

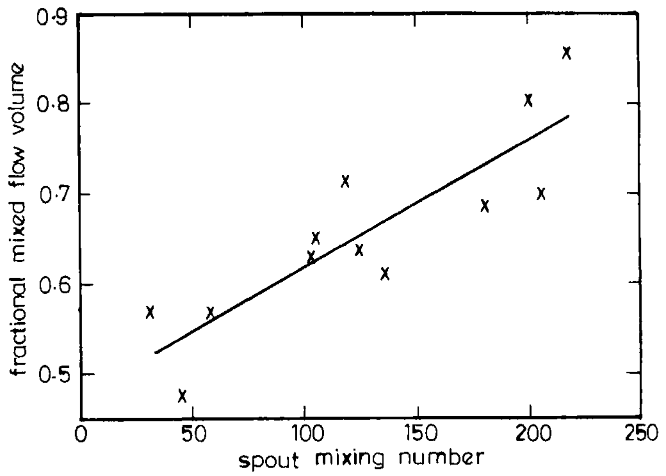

Figure 4. Fractional mixed flow volume vs. spout mixing number.

However, the following points are to be noted in the evaluation of α:

- The upper limit of H is H_m (maximum spoutable bed depth).
- The lower limit of U_0 is U_{ms} and the upper limit will be the operating fluid velocity corresponding to chaotic bed (region 5).
- When F_s is zero, it becomes a batch operation.

The values of α obtained in this work are given in Table 1. The plot of v_m/v versus α is shown in Figure 4. It is observed from this figure that higher the value of α the fraction of mixed flow volume in the bed is larger.

Conclusions

The results of this study indicate the following:

1) The spout mixing number may be used as a method of learning the extent of mixed flow volume in a continuously operated multiple spouted bed.

2) The fractional mixed flow volume in the bed increases with increasing spout mixing number.
3) In order to establish a definite relationship between α and v_m further studies are under progress.

Nomenclature

a	cell size, (mm)
d_p	particle size, (mm)
$I(\theta)$	internal age distribution
F_s	solids flow rate, (g/s)
H	static bed height, (cm)
H_m	maximum spoutable bed depth, (m)
l	particle length, (mm)
N	number of spout cells in the column
t	time, (s)
t_m	mean residence time, (calculated from exit age distribution), (s)
Q	air flow rate, (m^3/s)
U_0	superficial air velocity, (m/s)
U_{ms}	superficial air velocity at minimum spouting, (m/s)
v	total bed volume, (m^3)
v_m	mixed flow volume, (m^3)
v_p	plug flow volume, (m^3)
W	solids holdup in the bed, (kg)

Greek Symbols

α	spout mixing number
θ	t/t_m, dimensionless time
ρ_b	bulk density of solids, (kg/m^3)

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