Mathematical Modelling for Hydrodynamic Studies of Spouted Bed

B. Sahoo and A. Sahoo

***Abstract*—The hydrodynamic behaviour of the spouted bed has been studied by considering the different system parameters (viz. static bed height, spout diameter, particle size, gas velocity and particle density). Experiments were carried out using a Perspex column of 4 inch diameter. Attempts have been taken to develop correlations for the bed expansion / fluctuation ratios by varying different system parameters with the experimentally measured values of the bed dynamics on the basis of dimensional analysis. The calculated results of the expansion and fluctuation ratios were compared with the experimentally observed values. The standard deviations were found to be 8.45 and 9.98 respectively. A computer programme was also written for the calculation of these bed dynamics theoretically. Theoretical results thus obtained through computer programming are compared with the calculated values obtained through the developed correlations on the basis of dimensional analysis approach as well as with the experimentally observed values of bed dynamics.**

Index Terms—spouted bed, expansion ratio, fluctuation ratio, dimensionless analysis.

I. INTRODUCTION

The spouted bed and spouting were coined at the National Research Council of Canada in 1954 by Gishler and Mathur [1]. These investigators developed this technique initially as a method for drying wheat. Spouted bed apparatuses are already used in some technical areas where intense contact of gas-particle systems is required. The spouted bed technique is a variant of fluidization. The gas is injected vertically through a centrally located small opening at the base of the vessel. If the gas injection rate is high enough, the resulting high velocity jet causes a stream of particles to rise rapidly in a hollowed central core within the bed of solids. This system is termed as a spouted bed, the central core is called a spout, and the peripheral annular region is referred to as the annulus. The term fountain will be used to denote the mushroom-shaped zone above the level of the annulus. The use of spouted bed reactors for several chemical processes - coal carbonization, shale pyrolysis, ore roasting, cement clinker production, and thermal cracking of petroleum - has also received attention. The main advantage of spouted bed is that it is capable of performing certain useful cyclic operations on solid particles which cannot be performed in a fluidized bed due to its comparatively random particle motion. The other advantages of the spouted compared to other techniques of gas-particle contact is the possibility of achieving more intense heat- and mass-transfer conditions.

Ms. Brahmotri Sahoo is a M. Tech. student. This work is part of her M. Tech. thesis work. Email: bsahooch24nit@gmail.com
Dr. Abanti Sahoo is working as an Associte Professor in Chemical Engg, at NIT Rourkela, India. She is the supervisor of Ms. Brahmotri Sahoo. E-Mail: abantisahoo@gmail.com. Paper received in Feb-2011 and revised in April-2011.

II. LITERATURE SURVEY

The spouting and its stability, operating condition, spouting bed height along with the changing phenomenon from spouting to bubbling, slugging etc. as shown in Fig.-1 depends on many factors like effect of particle size, orifice size of spouting fluid, flow rate of fluidizing fluid, bed height and the density of particle used. For a given solid material contacted by a specific fluid in a vessel of fixed geometry, there exists a maximum spoutable bed depth H_m, beyond which the spouting action does not exists but it is replaced by a poor quality fluidization. The minimum spouting velocity at this bed depth can be 1.25 to 1.5 times greater than the corresponding minimum fluidization velocity, $U_{mf.}$

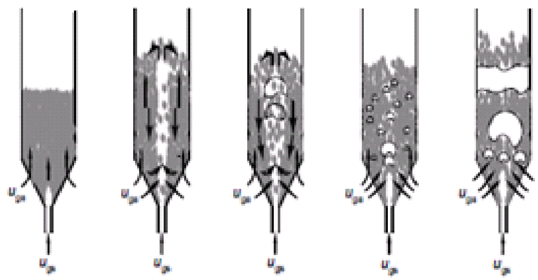

Fig.-1: Spouting behavior of the bed

The bed expansion and fluctuation ratios are used to describe the characteristics of bed height during fluidization process as mentioned below.

$$R = \frac{(H_{max} + H_{min})}{2 * H_s} \quad (1)$$

$$r = \frac{H_{max}}{H_{min}} \quad (2)$$

Ozalar et al. [2] used an optical fibre probe to study the effect of operating conditions (base angle, gas inlet diameter, stagnant bed height, particle diameter and gas velocity) on particle velocity in the three zones of spouted beds: spout, annulus and fountain [2]. They have drawn maps of velocity vector throughout the bed from the experimental and calculated values of particle velocities and determined zones of preferential solid cross-flow into the spout.

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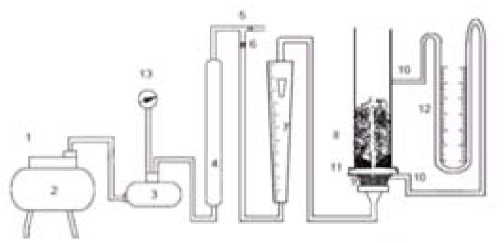
The time, frequency and phase space analyses of pressure measurements were compared in different spouted beds [3]. The experiments were carried out in different constructions of spouted bed apparatus, operated under ambient conditions and under different spouting regimes. A treatment technique using the Fast Fourier Transformation of measured pressure fluctuations was developed to create plots describing the bed behaviour evolution from fixed to slugging bed. At the beginning of stable spouting the amplitude of pressure fluctuations is observed to be uniform and small.

A novel annular spouted bed had been developed consisting of two homocentric upright cylinders with different diameters [4]. The nozzles and V-shaped deflectors were located in the bottom of annular space between the inner and outer cylinders. The effects of hold-up, bed material, total flow rate and nozzle structure on the hydrodynamic characteristics of the novel annular spouted bed were investigated. The results show that there exist three different zones for the particle flow in the annular spouted bed: the moving packed zone, the dense-phase spouted fluidizing zone and the dilute-phase zone. With the increase of hold-ups, the height of the dense-phase spouted fluidizing zone tends to increase in the annular spouted bed, while the moving packed zone is only limited within the V-shaped deflector

Bacelos and Freire, [5] carried out an experimental investigation to evaluate the stable spouting regime in conical spouted beds using four particle mixtures: a reference (mono-particles), a binary mixture and two ternary mixtures with flat and Gaussian distributions respectively, using a high-viscosity Newtonian fluid and glycerol. They selected mixtures of particle sizes (d_p) ranging from 1.09 to 4.98mm and particle size ratios (d_{pl}/d_{ps}) ranging from 1.98 to 4.0. It has been observed from experimental data that pressure fluctuation signals of the bed as indicated by changes in their standard deviations, provide suitable information to identify the range of operational conditions for stable spouting. For glycerol in the spouting regime, the standard deviation is noted to increase with increasing glycerol concentration due to the growth of inter particle forces.

III. EXPERIMENTATION

The experimental set-up as shown in Fig.- 2 consists of many parts such as an air compressor of capacity 25 kgf/cm^2, an air accumulator for storing the compressed air from compressor, a rotameter in the range of 0 to 200 Nm^3/hr, a fluidized bed column of diameter 10cm, four different diameters of distributor plates, a U-tube mercury manometer and valves like gate valve and globe valve. The experiment has been carried out to describe the characteristics of bed height during fluidization process. The distributor plates of spout diameter of 2.5, 3.0, 3.5, 4.0cm were used. These plates were made up of card boards by making a hole at the centre. This plate is tightly attached to the column with the help of the gasket so that there is no leakage of air. The screen of very fine size was put just below the distributor to prevent the backflow of bed materials. The rota meter was used for measuring the air flow rate passing to the column. A U-tube manometer was used for measuring the pressure drop across the bed with the mercury as the manometric fluid.



1.	Compressor	2.	Recevier
3.	Contact pressure tank	4.	Silica gel tower
5.	By pass valve	6.	Line valve
7.	Rotameter	8.	Spouting
9.	Calming section	10.	Pressure tapping
11.	Distributor	12.	Manometer
13.	Pressure gauge		

Fig.-2: Experimental set-up

The experiments were carried out by passing air through the distributor plate by varying the different system parameters as discussed in scope of the experiment (Table-1). The expanded bed heights and bed manometer readings were noted down at different flow rates of the air.

TABLE-I : SCOPE OF THE EXPERIMENT

Materials	Hs/Dc	Dp/Dc	Di/Dc	Uo/Umf	ρs/ρf
glass beads	0.8	0.033	0.25	1.25	2211.809
glass beads	1.2	0.033	0.25	1.25	2211.809
glass beads	1.6	0.033	0.25	1.25	2211.809
glass beads	20	0.033	0.25	1.25	2211.809
glass beads	0.8	0.026	0.25	1.25	2211.809
glass beads	0.8	0.022	0.25	1.25	2211.809
glass beads	0.8	0.017	025	1.25	2211.809
glass beads	0.8	0.033	0.3	1.25	2211.809
glass beads	0.8	0.033	0.35	1.25	2211.809
glass beads	0.8	0.033	0.4	1.25	2211.809
glass beads	0.8	0.033	0.25	1.15	2211.809
glass beads	0.8	0.033	0.25	1.35	2211.809
glass beads	0.8	0.033	0.25	1.5	2211.809
glass beads	0.8	0.033	0.25	1.25	2211.809
Al balls	0.8	0.033	0.25	1.25	2530.459
Mustard	0.8	0.033	0.25	1.25	1030.928
Sago	0.8	0.033	0.25	1.25	1255.858

IV. RESULTS

The following correlations have been developed for the bed expansion and fluctuation ratios by correlating different system parameters with the experimentally observed values.

$$R = 0.014\left(\frac{H_s}{D_c}\right)^{-0.006}\left(\frac{d_p}{D_c}\right)^{-0.241}\left(\frac{D_i}{D_c}\right)^{0.181}\left(\frac{\rho_s}{\rho_f}\right)^{0.759}\left(\frac{U_o}{U_{ms}}\right)^{0.487} \quad (3)$$

$$r = 0.002\left(\frac{H_s}{D_c}\right)^{-0.046}\left(\frac{d_p}{D_c}\right)^{-0.369}\left(\frac{D_i}{D_c}\right)^{0.204}\left(\frac{\rho_s}{\rho_f}\right)^{0.807}\left(\frac{U_o}{U_{ms}}\right)^{0.683} \quad (4)$$

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V. DISCUSSION

The hydrodynamic studies of different bed materials (such as glass beads, Al balls, sago and mustard seeds) were carried out using spouted bed. The bed expansion and fluctuation ratios of these materials are calculated as per the equations (1) and (2) respectively.

Experiments were carried out by varying the system parameters like density, static bed heights (8, 12, 16, and 20cm), spout velocity, particle diameter and spout diameters. For each experiment the variations of pressure drop against the superficial gas velocity were plotted of which a sample plot is as shown in Fig.-3. It is observed that pressure drop in the bed gradually increases with increase in velocity upto certain point, goes to the maximum then decreases but the height of the expanded bed observed to be constant. By further increasing the air velocity the pressure drop decreases upto certain point and then remains almost constant where the bed was noticed to be fluidizing completely. The corresponding velocity at which the pressure drop is constant is noted as the minimum spout velocity.

From Fig-3, the minimum spout and fluidization velocities are calculated. It is observed that in the case of glass beads of size (-5+6) the minimum spout velocity ranges from 42 to 44cm/sec, size (-6+7) the velocity ranges from 40 to 42cm/sec and for (-7+8) and (-8+12) it ranges from 38 to 40 and 32 to 36 cm/sec respectively due to the weight of the solids and the height of static beds. These variations of spout velocity are due to the variation in particle size.

Then effect of various system parameters (like H_s/D_c , D_i/D_c , U_o/U_{mf} , ρ_s/ρ_f , d_p/D_c) on bed expansion and fluctuation ratios are observed which are considered for the development of correlations as shown in Fig.- 4 and Fig.- 5.

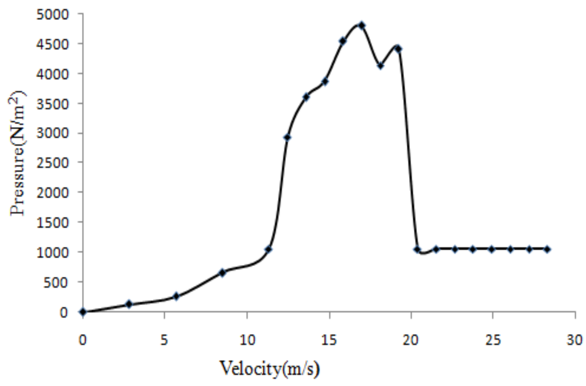

Fig.-3: Pressure drop profile

From the Fig.- 4 and Fig.-5, it was observed that with the increase in the static bed height, the expansion and the fluctuation ratios first decrease and then increase. In the case of particle size with the decrease in size the expansion and fluctuation ratio first increase and then decrease. With the increase in spout diameter the expansion ratio increases but the fluctuation ratio first increases, then decreases to some extent and again increases. In the case of rising values of flow rate the expansion as well as the fluctuation ratio both increase. The effect of particle density on the bed expansion and fluctuation ratios was not prominent as no clear trend is observed in the correlation plot. This needs further investigation into a wider variety of materials.

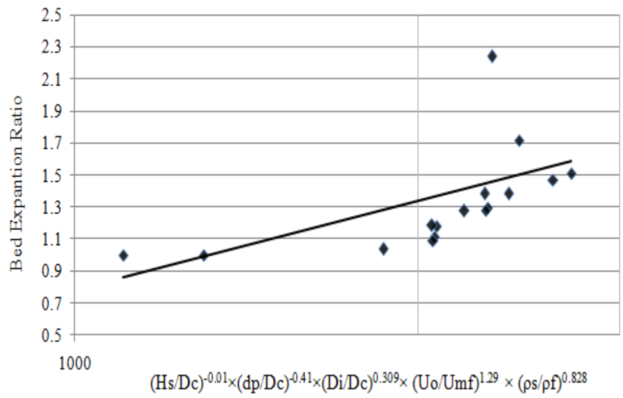

Fig.-4: Correlation plot for Bed Expansion ratio

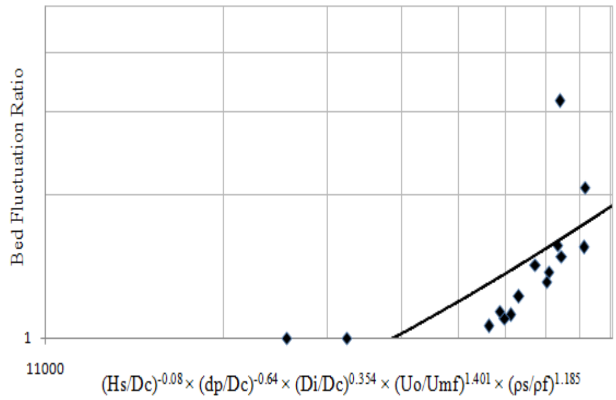

Fig.-5: Correlation plot for Bed Fluctuation ratio

Correlations were developed for the bed expansion and fluctuation ratios on the basis of dimensionless analysis approach by varying different system parameters (Eq.-3 and Eq.4). The overall changes in values of bed expansion and fluctuation ratios were observed from the developed correlations. With the increase in static bed height and particle size, both the expansion and fluctuation ratio decease but with the increase in spout diameter, flow rate, and density of particle the expansion and fluctuation ratios increase. Calculated values of bed expansion and fluctuation ratios obtained through Eqs. -1 and 2 are compared against the experimental values. The standard deviations were found to be 8.45 and 9.98 respectively. Again the calculated values of bed expansion and fluctuation ratios obtained through computer programming which are compared with those obtained from experimentation as well as those calculated by dimensionless analysis method as shown in Fig.-6(A) and (B). A flowchart was developed as shown in Fig.-7 for the programming.

VI. CONCLUSION

The calculated values of the bed expansion and fluctuation ratios were compared with the experimentally observed values and with values obtained through computer programming. The

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percentage of deviations is approximately between +15 to -15. The standard deviations for the bed expansion and fluctuation ratios were found to be 8.45 and 9.98 respectively which validates the developed correlations. This indicates that these correlations can be used suitably over a wide range of parameters. These results are in good applicability of the developed correlations for design of industrial spouted bed reactors where these can be used as basis of designs. Pilot plant units can suitably be designed by scaling up the laboratory units with certain modifications.

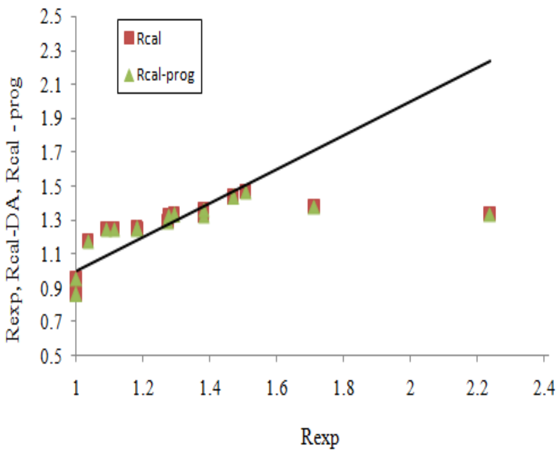

Fig.-6(A): Comparison plot of calculated bed expansion ratio values against the experimental values

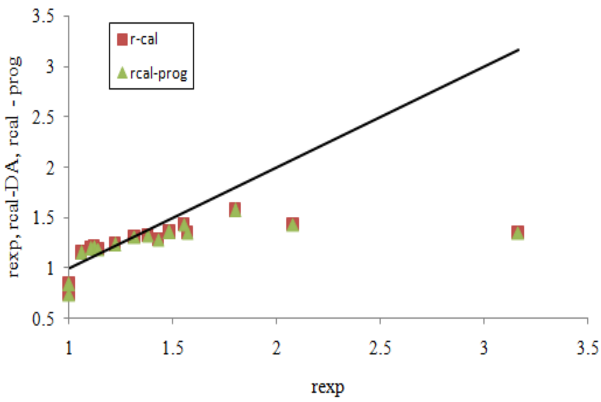

Fig.-6(B): Comparison plot of calculated bed fluctuation ratio values against the experimental values

VII. NOMENCLATURE

Hs	:	Static bed height, cm
Dc	:	Column diameter, cm
Di	:	Spout diameter, cm
dp	:	Particle diameter, mm
ρ_s	:	Particle density, kg/m^3
ρ_f	:	Air density, kg/m^3
Uo	:	Superficial velocity of air, cm/sec
Umf	:	Minimum spout velocity, cm/sec
R	:	Bed expansion ratio
r	:	Bed fluctuation ratio

Subscript:

max	:	Maximum values
min	:	Minimum values
avg	:	Average
exp	:	Experimentally observed values
cal	:	Calculated values
DA	:	Dimensionless Analysis
Prog	:	MATLAB programming

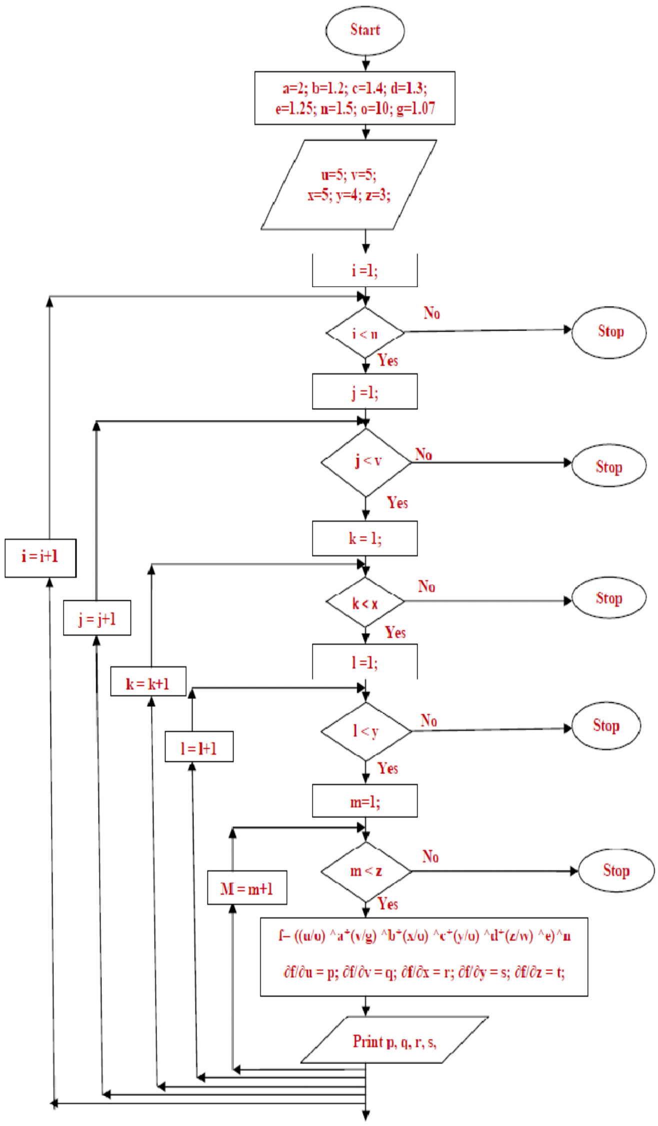

Fig.-7: Flowchart for MAT LAB Programming

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