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Hydrodynamic studies of cocurrent three phase fluidization using response surface method

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$Min \sum_{i=1}^{n} w_i . x_i$

$s.t\ \ A_{(n+w)\times n} X_{(n+w)\times 1}$

$Min \sum_{i}^{n} w_i . x_i$

$s.t\ \ y = A_{n\times n} X_{n\times 1} \geq b_{n\times 1}$

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ABSTRACT

With an aim to study the hydrodynamic characteristics of a cocurrent solid-liquid-gas phase fluidized bed, experiments were conducted using 3 different sizes of gypsum particles, water and air as three respective phases. The characteristics studied were pressure drop and solid, liquid, gas holdups, which were observed to be influenced by three factors namely particle size and superficial velocities of gas and liquid. The Response surface Methodology was applied to investigate the individual and combined effect of the three factors on hydrodynamics characteristics. An attempt has been made to develop quadratic models for pressure drop and phase holdups. The predicted values were compared with experimental values which gave a satisfactory fit with R^2 values around and above 0.95, indicating that the values predicted by the models were in good agreement with the experimental values.

Introduction

The field of fluidization has experienced massive development since the launch of the Winkler's process. The process was further developed and applied successfully to various applications such as FCC, Metallurgical processes, Sohio process, synthesis of polymers, combustion, drying, biochemical processes and waste water treatment[1 – 5]. Similar to the industrial development, extensive scholastic research has also been carried out in fluidization. Relative to other multiphase contactors, there has been plenty of works available in the three phase fluidization with most studies directed towards understanding the hydrodynamic characteristics [6 - 8], since the hydrodynamics plays a vital role in optimizing the performance of the system. Several works have been so far done for the prediction of the hydrodynamic characteristics such as bed porosity, phase holdups and pressure drop and various correlations have been proposed based on the experimental studies [9 – 11, 20].

Still the field is being under investigation for inclusive identification of the behavior and characteristics of fluidized beds under rational circumstances. The advancement in computational methods and simulation tools has led to carry out the studies on a further comprehensive manner. Optimization of bed characteristics is ultimately a tough task. However some of the characteristics such as porosity, gas holdup and pressure drop have been successfully optimized by researchers using tools like Genetic Algorithm [12]. Response Surface Method (RSM) is one of the statistical tools which have a wide application in the field of biochemical and chemical processes.

In this work, an effort has been made to apply the design of experiment and response surface method to study the hydrodynamic characteristics of a cocurrent three phase fluidized bed. In order to conduct the study, different sizes of gypsum particle with air and water as solid-gas-liquid phases have been used respectively. From the obtained data, an attempt has been made to develop a quadratic model for the hydrodynamic characteristics of three phase fluidized bed using response surface method.

Materials and Methods

Experimental details

The experimental setup consists of a liquid storage tank from which water is pumped by a centrifugal pump. The flow rate of water and air is measured using a Rotameter and an Orifice meter respectively. A schematic diagram of experimental setup is shown in the Figure 1. A vertical Perspex column, 1.6 m tall with internal diameter of 5.4×10^{-2} m and outer diameter of 6×10^{-2}m is used, which consists of three sections - the gas-liquid distributor section, test section and gas-liquid disengagement section. The properties of fluids used are shown in Table 1. The gas-liquid distributor is located at the bottom of the test section and designed in such a manner that uniform distribution of the liquid and gas can be maintained in the column. The circular gas distributor section made of copper is provided with four protrusions each having I.D. 1.4 $\times10^{-2}$m. The liquid inlet pipe of 2.5 $\times10^{-2}$m I.D. is located centrally in this section. The outlet of the test section is at a height of 1.5 m and has a mesh attached to it in order to retain the entrained particles. There are two pressure tapings provided at the top and the bottom of the test section which are connected to the manometer for pressure drop measurement. Mercury and Carbon tetra chloride are used as manometer liquid for measuring the pressure drop in the Rotameter and the Orifice meter respectively. The hydrodynamics studies are carried out for various sizes of gypsum particles. The liquid velocity is kept constant and the gas velocity is varied. After steady state is attained for each gas velocity, the fluidized bed height and manometer readings are

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noted. The same procedure is repeated for different liquid velocities. The effect on phase hold ups and pressure drop is studied for different gypsum particle sizes.

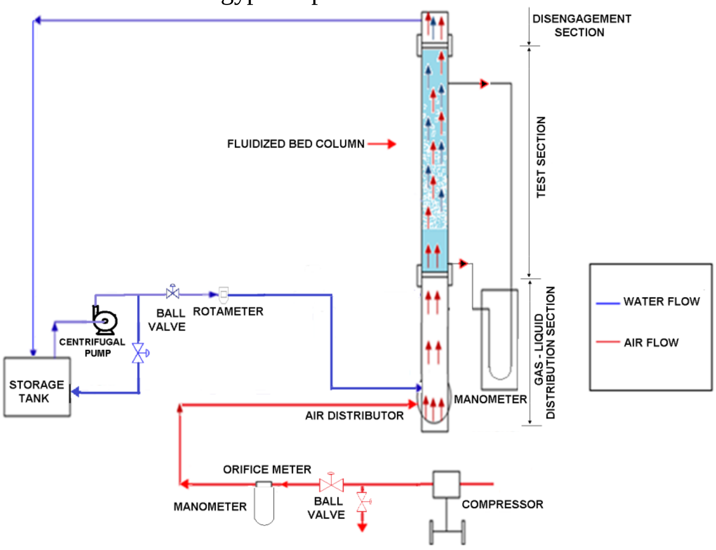

Figure 1. Experimental setup

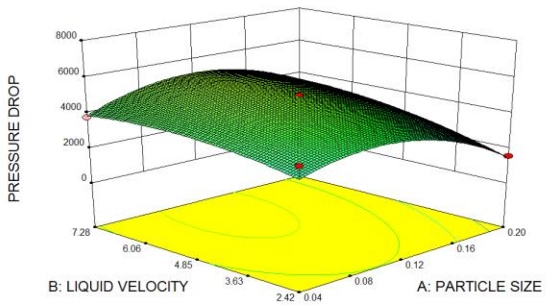

Fig 2a

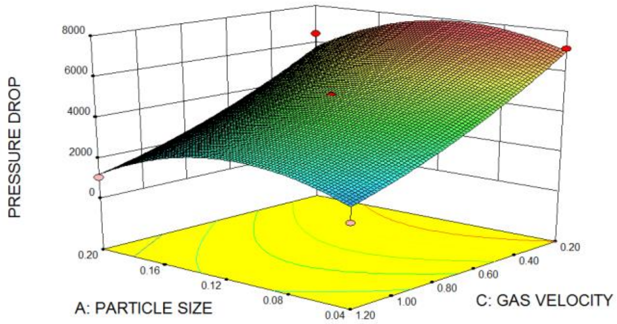

Fig 2b

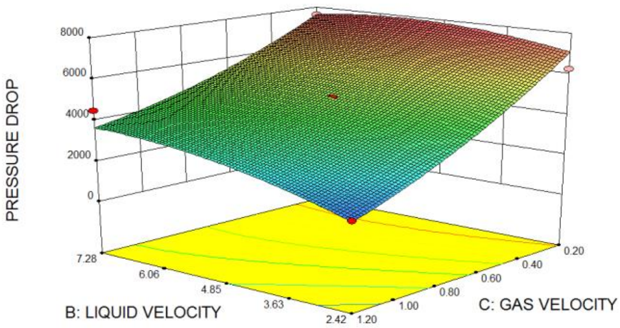

Fig 2c

Figure 2. Combined effect of variables on pressure drop – a) effect of liquid velocity and particle size, b) effect of particle size and gas velocity, c) effect of gas and liquid velocities

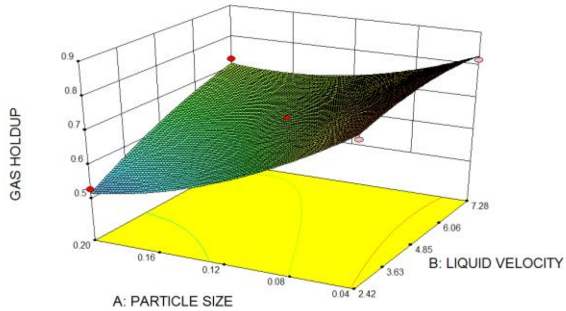

Figure 3.a

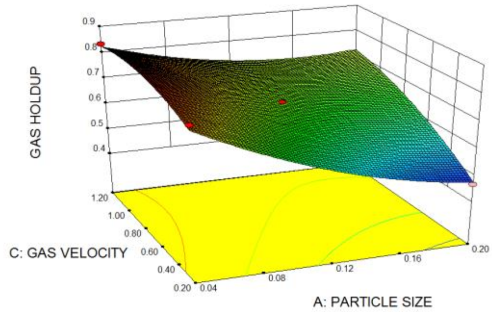

Figure 3.b

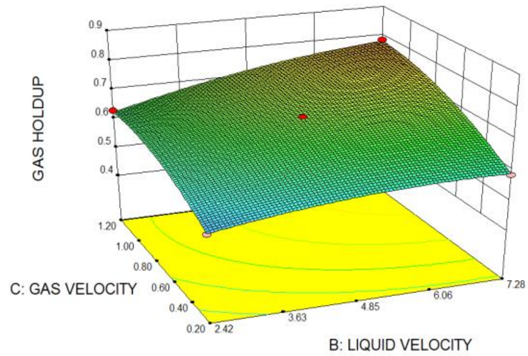

Figure 3.c

Figure 3. Combined effect of variables on gas holdup– a) effect of liquid velocity and particle size, b) effect of particle size and gas velocity, c) effect of gas and liquid velocities

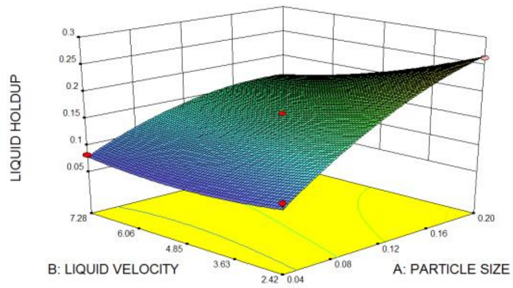

Figure 4.a

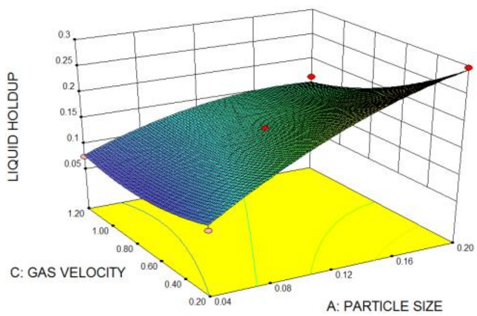

Figure 4.b

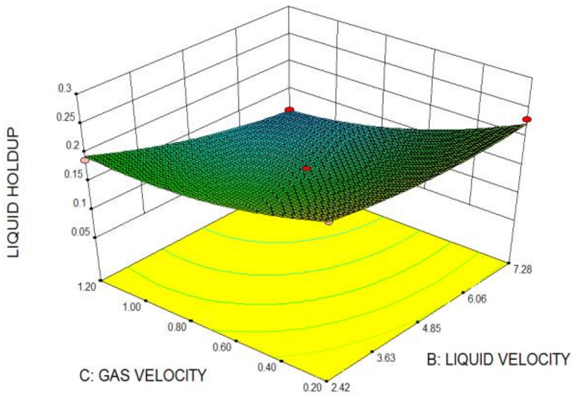

Figure 4.b

Figure 4. Combined effect of variables on liquid holdup– a) effect of liquid velocity and particle size, b) effect of particle size and gas velocity, c) effect of gas and liquid velocities

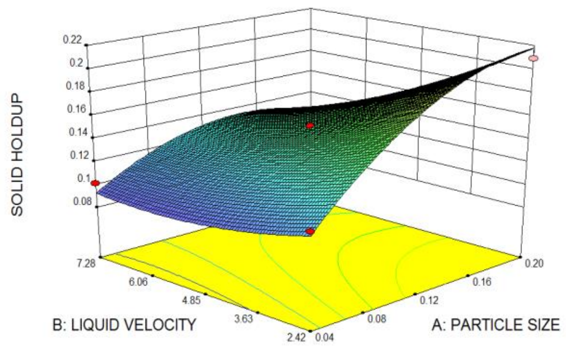

Figure 5.a

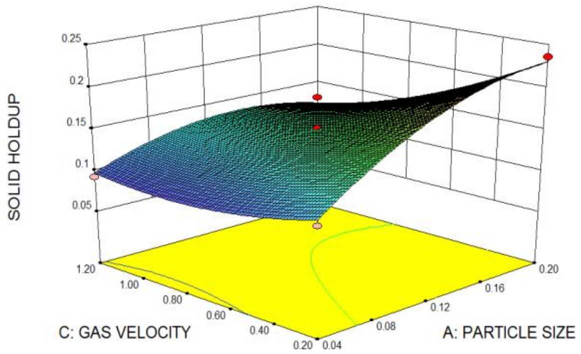

Figure 5.b

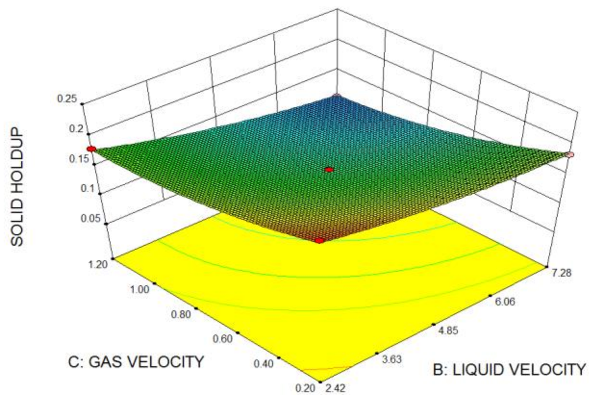

Figure 5.c

Figure 5. Combined effect of variables on solid holdup– a) effect of liquid velocity and particle size, b) effect of particle size and gas velocity, c) effect of gas and liquid velocities

Design of experiments

The design of experiments is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions [13]. The task starts with identifying the input variables and the response (output) that is to be measured. For each input variable, a number of levels are defined that represent the range for which the effect of that variable is desired to be known. In this study, the Box–Behnken experimental design was chosen for finding out the relationship between the response function variables such as Solid, Liquid, Gas holdups and Pressure drop for three different sizes of gypsum particles. Box–Behnken design is rotatable second-order designs based on three-level incomplete factorial designs. The special arrangement of the Box–Behnken design levels allows the number of design points to increase at the same rate as the number of polynomial coefficients. For three factors, for example, the design can be constructed as three blocks of four experiments consisting of a full two-factor factorial design with the level of the third factor set at zero. However, it can also be viewed as consisting of three interlocking 2^2 factorial design and a central point. It has been applied for optimization of several chemical and physical processes.

For the chosen experimental design, a total of 17 experimental runs are needed. The reason for selecting three-level design was that the third level for a factor facilitates investigation of a quadratic relationship between the response and each of the factors. For the hydrodynamics studies, the particle sizes, liquid and gas velocities were taken as independent input variables whilst solid holdup (ε_s), liquid holdup (ε_l), gas holdup (ε_g) and pressure drop (ΔP) as response variables. The experiment was designed with variables ranging from a higher coded value of 1 to a lower code value of - 1. The factor variables and their ranges are given in Table 2. Summary of actual design of experiment is given in Table 3.

Response Surface Methodology

Response Surface Methodology (RSM) is a collection of statistical and mathematical techniques useful for optimizing objective functions. The methodology is based on approximation of the objective function by a low order polynomial on a small sub-region of the domain [14]. Given a response variable Y and k factors, X1,...,Xk, the main purpose of RSM is to find the combination of factor levels to achieve the optimal response. For computational convenience, the variables are usually converted to coded or design variables, x1,…,xk, standardized so that the design centre is at the point (x1,…,xk) = 0. Moreover it is assumed that the true response is a function of the levels of the k design variables, f(x1, x2,…, xk), called the true response function [15]. In the present work the RSM was applied to investigate/study the effect of input variables on the phase holdups and pressure drop. Following the full factorial design, 17 values for each response were obtained and were used to estimate the coefficients of reduced and full second order models. Based on the analysis, the effects (main and interaction) that were statistically significant were included in the developed models. A quadratic response surface with design variable inputs x1 and x2 and output variable y was formulated as:

$$y = \beta o + \beta 1x1 + \beta 2x2 + \beta 3x21 + \beta 4x22 + \beta 5x1x2$$

where y is the response function and βi (i=0,…,5) are the unknown coefficients that were estimated by least squares fitting of the model to the experimental results obtained at the design points. As in fitting any regression model, the analysis of the residuals from the fitted model is necessary to determine the adequacy of the least squares fit. This was achieved by an estimate of R-squared values. The normal probability plot becomes essential as it provides information about the absence of any serious violation of the normality assumption. For this assumption to be true the points in the plot will roughly form a straight line. After validation of the models, a visual interpretation of the functional relations was made by graphic illustrations of the response surfaces.

Results and Discussion

Interpretation of surface graphs

The response surface methodology was applied to hydrodynamic studies in three-phase fluidization and the results were presented in surface plots. This study was carried out to check the influence of various operating parameters on pressure drop and phase holdups. The effects of variables on the hydrodynamic characteristics of gypsum are given in Figures 2-5. The interaction between varying gas and liquid velocity along with particle diameter is given in 3-dimensional surface plots.

Pressure drop evaluation

It can be ascertained from the surface plot that the ΔP decreases with increase in particle size and gas velocity. The decrease in pressure drop may be attributed to the back mixing at high gas velocities due to high turbulence and possibly due to the influence of distribution. The increase in superficial liquid velocity results in an increase of ΔP. (Figure 2). The observed trends are in accordance with the earlier observations of H.M.Jena et al and Zhaolin Wang et al [16, 17].

Gas holdup evaluation

The gas holdup decreases significantly with an increase in particle size whereas it slightly increases with increase in both superficial velocities (Figure 3). Similar trends were observed with the findings of Sivakumar V et al [18]. This trend may be explained as follows. The gas and liquid phases are moving cocurrently through the column; however the liquid phase velocities are higher than gas phase velocities obtained in this work. So, since the gas passage through the column is slower, more gas accumulation occurs in the column compared to liquid accumulation resulting in an increase in the ε_g.

Liquid holdup evaluation

Figure 4 shows the surface plots for the ε_l. Contrary to decrease in ε_g with increase in particle size, ε_l increases with increase in particle size. Similarly, it decreases with increase in both superficial velocities. These trends can be explained with the similar reason as stated in section 3.1.2. Since the liquid passage through the column is faster, less liquid accumulation occurs in the column and this accumulation decreases with increase in liquid velocity, thus resulting in the reduction of liquid holdup.

Solid holdup evaluation

Analogous to ε_l, ε_s increases with increase in particle size whilst it decreases marginally with increase in both superficial velocities (Figure 5). Ik-Sang Shin et al [19] reported similar trends. These trends may be explained as follows; when either liquid velocity or gas velocity is increased, there would be higher drag forces exerted on the solid particles, leading to more bed expansion; this results in reduction of solids holdup in the expanded bed.

Fitted Regression models

Based on the factor variables and responses chosen to study (Tables 2 and 3), the model coefficients were computed by the least square method. The coefficients and corresponding P values obtained were shown in table. Based on the regression coefficients, the mathematical relationship between variables and responses were determined as:

The predicted pressure drop and phase holdups, using the above four equations 1 – 4 was compared with experimental values and given in Table 4 and Figure 6. It can be noticed from the figure that the equation predictions adequately match the experimental values within 5% error.

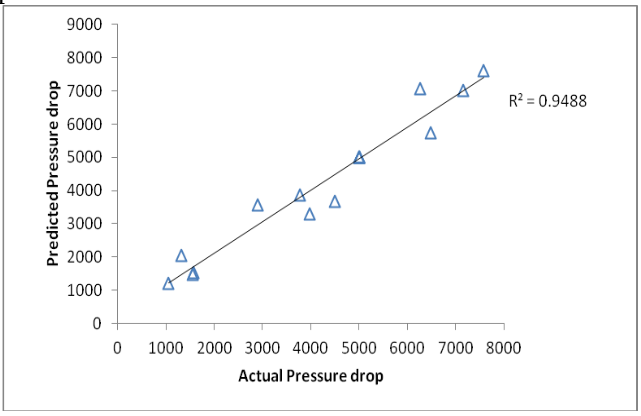

Figure 6.a

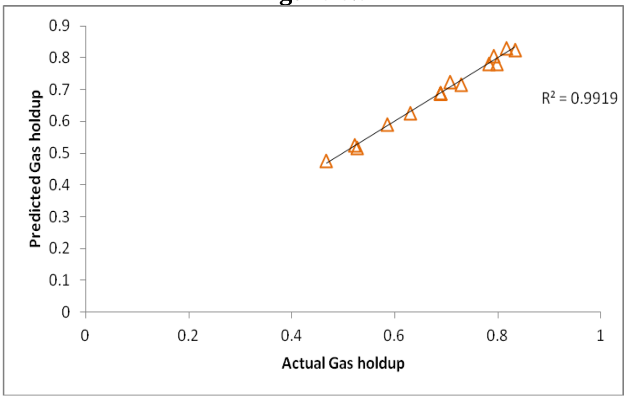

Figure 6.b

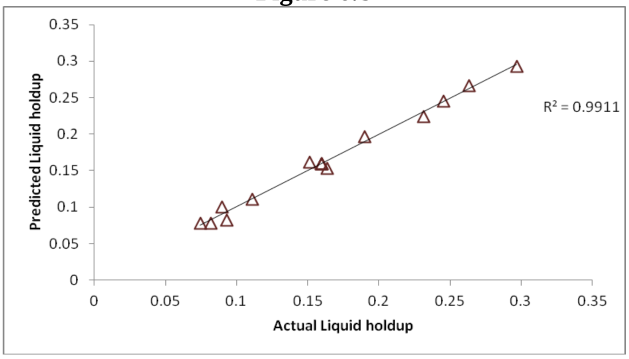

Figure 6.c

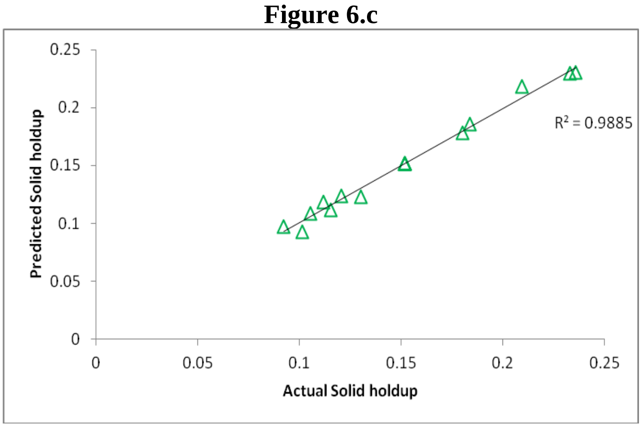

Figure 6.d

Figure 6. Predicted vs Actual values – a) Pressure drop; b) Gas holdup; c) Liquid holdup; d) Solid holdup

Table 1. Properties of fluids used

Fluid	Density (Kgm^{-3})	Viscosity (Nsm^{-2})
Air	1.15	0.000019
Water	995.6	0.0085

Table 2. Range of factor variables

Factor	Name	Units	Minimum (-1)	Maximum (1)	Mean (0)
A	Particle Size	cm	0.04	0.2	0.12
B	Liquid Velocity	cm/s	2.42	7.28	4.85
C	Gas Velocity	cm/s	0.2	1.2	0.7

Table 3. Actual design of experiments and responses

Std	Run	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4
		A:PARTICLE SIZE	B:LIQUID VELOCITY	C:GAS VELOCITY	PRESSURE DROP	GAS HOLDUP	LIQUID HOLDUP	SOLID HOLDUP
		cm	cm/s	cm/s	Pa	No Unit	No Unit	No Unit
1	7	0.04	2.42	0.7	3971.63	0.7920	0.0929	0.1152
2	17	0.2	2.42	0.7	1560.72	0.5271	0.2634	0.2094
3	3	0.04	7.28	0.7	3776.85	0.8170	0.0817	0.1013
4	14	0.2	7.28	0.7	2898.19	0.7284	0.1513	0.1203
5	5	0.04	4.85	0.2	7150.98	0.7986	0.0899	0.1115
6	1	0.2	4.85	0.2	6481.12	0.4673	0.2968	0.2359
7	4	0.04	4.85	1.2	1326.16	0.8335	0.0743	0.0922
8	10	0.2	4.85	1.2	1052.65	0.7067	0.1634	0.1299
9	16	0.12	2.42	0.2	6253.97	0.5215	0.2454	0.2331
10	13	0.12	7.28	0.2	7577.62	0.5849	0.2313	0.1838
11	12	0.12	2.42	1.2	1571.88	0.6301	0.1897	0.1802
12	8	0.12	7.28	1.2	4494.94	0.7835	0.1110	0.1054
13	11	0.12	4.85	0.7	4999.90	0.6885	0.1598	0.1518
14	6	0.12	4.85	0.7	4999.90	0.6885	0.1598	0.1518
15	2	0.12	4.85	0.7	4999.90	0.6885	0.1598	0.1518
16	15	0.12	4.85	0.7	4999.90	0.6885	0.1598	0.1518
17	9	0.12	4.85	0.7	4999.90	0.6885	0.1598	0.1518

Table 4. Actual vs Predicted values

Std order	Pressure Drop		Gas Holdup		Liquid Holdup		Soli Holdup	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	3971.63	3290.35	0.7920	0.8063	0.0929	0.0821	0.1152	0.1117
2	1560.72	1465.99	0.5271	0.5152	0.2634	0.2666	0.2094	0.2182
3	3776.85	3871.57	0.8170	0.8289	0.0817	0.0785	0.1013	0.0925
4	2898.19	3579.47	0.7284	0.7141	0.1513	0.1621	0.1203	0.1238
5	7150.98	7008.19	0.7986	0.7814	0.0899	0.1003	0.1115	0.1184
6	6481.12	5751.78	0.4673	0.4763	0.2968	0.2932	0.2359	0.2305
7	1326.16	2055.50	0.8335	0.8245	0.0743	0.0779	0.0922	0.0975
8	1052.65	1195.44	0.7067	0.7239	0.1634	0.1530	0.1299	0.1230
9	6253.97	7078.04	0.5215	0.5244	0.2454	0.2458	0.2331	0.2297
10	7577.62	7625.68	0.5849	0.5902	0.2313	0.2241	0.1838	0.1857
11	1571.88	1523.82	0.6301	0.6248	0.1897	0.1969	0.1802	0.1783
12	4494.94	3670.87	0.7835	0.7806	0.1110	0.1106	0.1054	0.1088
13	4999.90	4999.90	0.6885	0.6885	0.1598	0.1598	0.1518	0.1518
14	4999.90	4999.90	0.6885	0.6885	0.1598	0.1598	0.1518	0.1518
15	4999.90	4999.90	0.6885	0.6885	0.1598	0.1598	0.1518	0.1518
16	4999.90	4999.90	0.6885	0.6885	0.1598	0.1598	0.1518	0.1518
17	4999.90	4999.90	0.6885	0.6885	0.1598	0.1598	0.1518	0.1518

$$Pressure\ Drop = 4999.9 - 529.12*A + 673.67*B - 2377.26*C + 383.06*A*B + 99.09*A*C + 399.85*B*C - 1459.96*A^2 - 488.09*B^2 + 462.79*C^2 \quad \text{--- (1)}$$

$$Gas\ holdup = 0.69 - 0.1*A + 0.055*B + 0.073*C + 0.044*A*B + 0.051*A*C + 0.023*B*C + 0.05*A^2 - 0.022*B^2 - 0.037*C^2 \quad \text{--- (2)}$$

$$Liquid\ holdup = 0.16 + 0.067*A - 0.027*B - 0.041*C - 0.025*A*B - 0.029*A*C - 0.016*B*C - 0.025*A^2 + 0.013*B^2 + 0.022*C^2 \quad \text{--- (3)}$$

$$Solid\ holdup = 0.15 + 0.034*A - 0.028*B - 0.032*C - 0.019*A*B - 0.022*A*C - 6.375E-003*B*C - 0.024*A^2 + 9.003E-003*B^2 + 0.015C^2 \quad \text{--- (4)}$$

Table 5. ANOVA table for the responses

Response	Source	Degrees of Freedom	Sum of squares	Mean square	F	P
Pressure drop	Model	9	63201655.6	7022406.17	14.400	0.001
	Residual	7	3413661.7	487665.96		
	Total	16	66615317.3			
Gas holdup	Model	9	0.186515	0.020723	95.813	<0.0001
	Residual	7	0.001514	0.000216		
	Total	16	0.188029			
Liquid holdup	Model	9	0.067158	0.007462	87.346	<0.0001
	Residual	7	0.000598	0.000085		
	Total	16	0.067756			
Solid holdup	Model	9	0.031164	0.003463	67.461	<0.0001
	Residual	7	0.000359	0.000051		
	Total	16	0.031524			

Table 6. R – Squared values

Response	R – Squared	Adj R – Squared	Adeq Precision
Pressure drop	0.9487556	0.88286995	12.0057766
Gas holdup	0.991948	0.981595	31.26191
Liquid holdup	0.991174	0.979826	30.36783
Solid holdup	0.988602	0.973948	25.11164

Analysis of variance

The ANOVA Tables (Table 5) can be used to test the statistical significance of the ratio of mean square due to regression and mean square due to residual error. The R^2 values can be computed as, R^2 = (Sum of squares attributed to the regression) / (Total sum of squares). The values thus found are around 0.95 and above, which implies that almost 95 % of the variability in the data for each models were explained by the models. The model adequacy has also been verified by the adjusted- R^2 value. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable for an ideal model. Table 6 indicates the ratios of adequate signals for each response model. Generally P values lower than 0.001 indicates that the model is considered to be statistically significant at the 99% confidence level. The ANOVA table indicates that the second-order polynomial model (equations 1 - 4) is significant and adequate to represent the actual relationship between the responses and the (transfer efficiency) variables, with small p value and high value of R^2 for pressure drop and phase holdups with values of 0.9487556, 0.991948, 0.991174 and 0.988602 respectively.

Conclusion

Experiments were carried out using gypsum, air and water as solid, gas and liquid phases for hydrodynamic studies in three-phase fluidization. It was observed that the pressure drop and phase holdups were significantly influenced by particle size, superficial gas and liquid velocities. The experimental data was analysed using response surface methodology and the effect of individual and combined parameters on pressure drop and phase holdups were analysed using the Box-Behnken method. Regression equations were developed for all responses. It was proved that the model predictions of the responses were in good agreement with the experimental observations.

Nomenclature

A	-	Particle size, cm
B	-	Liquid velocity, cm/s
C	-	Gas velocity, cm/s
I.D.	-	Inner diameter, m
O.D.	-	Outer diameter, m
$X_1,..X_k$	-	Factors
Y	-	Response Variable

Greek symbols

β_i	-	Coefficient
ε_g	-	Gas holdup
ε_l	-	Liquid holdup
ε_s	-	Solid holdup
ΔP	-	Pressure drop, Pa

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