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Gas hold-up, pressure drop and flow regime study in semi-batch PSRBC bubble column

Shakti Prasanna Khadanga[1], Deepak Kumar Samal[2]*, Prabina Kumar Patnaik[1] & Gopendra Kishore Roy[1]
[1]Department of Mechanical Engineering, GIET University Gunupur, Rayagada, Odisha- 765022, India
[2]Department of Chemical Engineering, Haldia Institute of Technology, Haldia, West Bengal-721 657, India
*E-mail: dksamal@hithaldia.ac.in

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The present investigation is aimed to give a new dimension to the bubble column hydrodynamic study such as gas hold-up, flow regime and total pressure-drop. Pressure swing rotating bubble cap (PSRBC) sparger is used for this purpose, which has a unique feature of self-rotating ability. Compressed air is supplied through the PSRBC sparger into the column of stationary water. Flow regime and gas hold-up of bubble column have been studied with various superficial air flow rates. Empirical and semi-empirical models have been developed for predicting gas hold-up, pressure drop and RPM for the PSRBC sparger bubble column in the present range of investigation. The calculated values from predicted models have been compared with the experimental values and the coefficients of correlations are found to be more than 0.97. The present hydrodynamic study on gas hold-up, pressure drop, flow regime and RPM may be found useful for the gas-liquid systems, where the gas phase is dispersed in liquid through bubbling manner.

Keywords: Flow regime, Gas hold-up, Hydrodynamics, Pressure swing rotating bubble cap (PSRBC), Sparger

Introduction

In the field of gas-liquid system, bubble column has its own identity for its simplicity in construction and low operating cost. The ‘bubbling’ is a preferable method of contacting the gas-liquid phases due to the creation of maximum inter-facial area which is helpful for performing chemical, biochemical, petrochemical operations and processes[1]. Mainly all the focus is centered for the study of flow regimes, gas hold-up and design of sparger for the bubble column[2]. Based on flow regime, the empirical correlations have been suggested by various researchers for mass transfer, heat transfer and other related studies in bubble column[3-8]. The gas hold-up in the bubble column has been studied by using various techniques for various flow regimes including simulation[9-11,15-16]. The empirical correlations for gas hold-up developed by researchers were summarized by Kantarci et al.[1]. The pressure difference method is widely adopted among the techniques used for gas hold-up measurement, due to simple, non-invasive and non-interrupt bubble column operation[16].

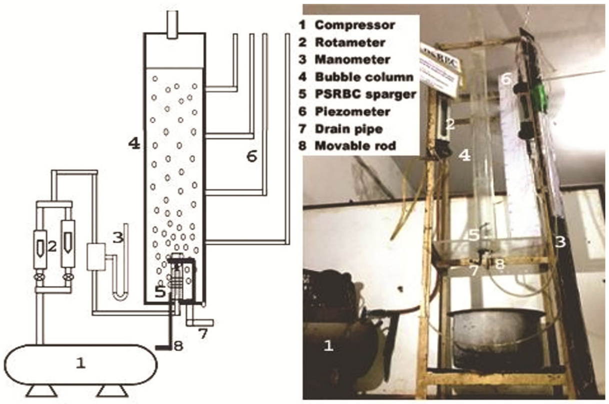
Bubble column performance is controlled by the gas phase, which is evident from literature[12]. Population of bubbles (gas hold-up) in a bubble column is an important parameter because of providing more inter-facial area for mass transfer operation, heat transfer and other related processes[14]. More especially when a gas phase employed as limiting reactant in batch, continuous or semi-batch reactor for gas-liquid reaction, the residence time is an important parameter for the conversion, which can be controlled by gas hold-up. Bubble column hydrodynamic study focusing on sparger design has gained lots of attention[12,14]. Bubble column has been extensively studied using various sparger designs for better performance, which in turn affects gas hold-up values[1]. The flow regime is classified mainly into three types’ viz. homogenous, transition and churn turbulent region in bubble column using fixed sparger[1-2]. The homogeneous regime is characterized by almost uniformly sized bubbles. In contrast, the heterogeneous regime is characterized by non-uniform bubble concentration[11].

Pressure swing rotating bubble cap (PSRBC) sparger was used for the present investigation. The design of PSRBC sparger made it unique among the family of sparger due to the self-rotating ability. PSRBC can perform the dual job as sparging and mixing simultaneously. All other gas spargers required a stirrer for rigorous mixing in gas-liquid system. Till date the PSRBC sparger’s complete hydrodynamic behaviour is not explored for application purposes in gas-liquid system. In the present investigation, PSRBC sparger[17-18] is used in a bubble column for gas hold-up, flow regime and pressure drop study, along with the development of correlations. Rotation of PSRBC sparger has been analyzed which in turn affects the intensity of gas-liquid mixing.

Experimental Section

Schematic and pictorial representations of the experimental setup are shown in Fig. 1a and 1b respectively. The test section was made up of acrylic column of 100 mm i.d. and 1800 mm height. Compressed air and tap water were used for the present study. Four Piezometers were provided at 250 mm apart from bottom at various locations of the bubble column for gas hold-up study by pressure difference method[2]. Two U-tube monometers were fixed with manometric fluids of mercury and water for high and low pressure drop measurement, respectively. Compressed air inlet was a straight nozzle (4 mm i.d. and 50 mm height) mounted vertically at the base of the bubble column. A vertical movable rod (2 mm diameter of 150 mm length) was also mounted on the bottom for keeping PSRBC sparger stationary and movable condition. Base of the bubble column has a provision for draining the liquid. 30 angular nozzles of 20 mm arc length and 1.8 mm i.d. were attached to the cylindrical cap of 120 mm height and 10 mm i.d. as shown in Fig. 2a, which represents pictorial view of the bottom part of bubble column. Internal guiding stainless-steel needle of 100 mm length and 0.4 mm diameter was fixed axially at the center and extended 10 mm beyond the top of the sparger as shown in Fig 2b. External support has been provided to the sparger on top extended part as shown in Fig 2a. Tachometer was used to record the RPM for this investigation.

The scope of the experiment is presented in Table 1. Test section was filled with 1100 mm height of water. The compressed air was supplied through rotameter at a constant flow rate to the bubble column with the help of PSRBC sparger. The manometer readings were recorded for various air flow rates, to analyze the pressure drop by the sparger and gas hold- up. The RPM of PSRBC sparger was recorded by tachometer for each air flow rate. Same procedure was repeated without rotation of sparger for comparative analysis. Flow regime was being classified under visual observation at various air flow rates.



(a) Schematic (b) Pictorial

Fig. 1 — (a) Schematic and (b) pictorial representations of the experimental setup

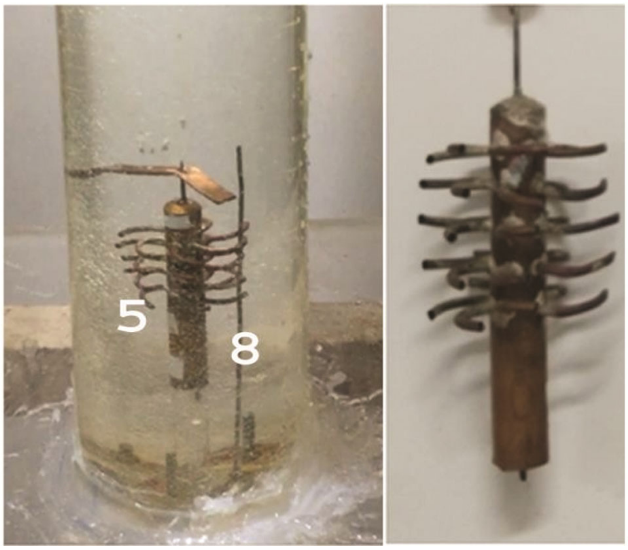


Fig. 2 — (a) Bottom of bubble column and (b) PSRBC sparger

Table 1 — Scope of experiment

System	Air and Water
PSRBC, ID & H (mm)	10 and 120
Inlet Air Supply Nozzle ID (mm)	04
Angular Nozzle ID and Arc Length (mm)	1.8 and 20
Bubble column (ID & H) (mm)	100 and 1800
Air Compressor, HP	2
Air flow meter, max^{m} LPM	50 & 200
Tachometer	5-digit display

Rate of kinetic energy used for the rotation of PSRBC is analyzed as:

Applying the conservation of energy between the inlet (1) and outlet (2) of angular nozzles (Fig. 3), For stationary sparger: $E_1^S = E_2^S$ (neglecting losses)

Fig. 3 — Top view of PSRBC

$$\Delta P_{ST} = \mu u_{1S}^2 \left[\left({A_1}/{A_2} \right)^2 - 1 \right] \qquad \ldots(1)$$

For rotating sparger: $E_1^R = E_2^R$ (neglecting losses)

$$\Delta P_{RT} = \mu u_{1R}^2 \left[\left({A_1}/{A_2} \right)^2 - 1 \right] + E_R \qquad \ldots(2)$$

For a given flow rate of air, $u_{1S} = u_{1R} = u$ (say)

Hence, $\Delta P_{ST} - \Delta P_{RT} = E_R = ({1}/{2})(m) \times (u_{SP})^2 = ({1}/{2})(\rho \times Q_g) \times (R \times 2\pi N)^2 = \emptyset(Q_g \times N^2) \ldots(3)$

Where, $\emptyset = ({1}/{2})(\rho \times R^2) 4\pi^2$

The constant of proportionality "$\emptyset$" depends on the geometrical and fluid properties of the system.

Results and Discussion

Sparger design affects the bubble column performance[1], as the gas-liquid inter-facial area is an important parameter for any gas-liquid or gas-liquid-solid system. In stationary sparger bubble column the pressure drop increases as gas flow rate increases, for which the regime transformation takes place quickly in bubble column. PSRBC sparger is one of its own kinds, which converts a part of total energy to rotational energy, which is contributing to the bulk mixing with keeping the bubbles in a particular regime for long period of time. Flow regime (visual observation) and gas hold-up (differential pressure method) of bubble column have been studied with various air flow rates with PSRBC sparger. Based on the experimental investigation and data processing thereof, gas hold-up, flow regime, RPM and total pressure drop of sparger are discussed in this section. Empirical and semi-empirical models have been developed for predicting gas hold-up RPM and pressure drop for the PSRBC sparger in the present range of investigation. The design of experiment for the gas hold-up, total pressure-drop and RPM of PSRBC sparger is given in Table 2 and 3.

Table 2 — Experimental design matrix and responses for Dry run

Q_g (m^3/min)	ΔP_{sta} (N/m^2)	ΔP_{rot} (N/m^2)	RPM
0	0	0	0
0.005	800.496	800.496	0
0.01	1334.16	1334.16	0
0.015	2134.656	2134.656	0
0.02	3201.984	3201.984	0
0.025	4536.144	4536.144	0
0.03	7204.464	6670.8	0
0.035	9605.952	8805.456	0
0.04	12007.44	10673.28	5
0.045	15476.26	13341.6	100
0.05	18678.24	16009.92	380
0.055	22680.72	20012.4	560
0.06	26683.2	24014.88	700
0.065	32019.84	28017.36	850
0.07	37356.48	32019.84	990
0.075	42693.12	37356.48	1080
0.08	48029.76	42693.12	1190
0.085	54700.56	48029.76	1300

Table 3 — Experimental design matrix and responses for Wet run

Q_g (m^3/min)	ΔP_{sta} (N/m^2)	ΔP_{rot} (N/m^2)	RPM
0	0	0	0
0.005	3335.4	3335.4	0
0.01	6670.8	6670.8	5
0.015	9339.12	9072.288	20
0.02	12541.1	12007.44	36
0.025	15476.26	14008.68	52
0.03	18411.41	16009.92	72
0.035	21613.39	18678.24	90
0.04	24681.96	21346.56	110
0.045	28017.36	24014.88	131
0.05	32019.84	26683.2	157
0.055	37356.48	29351.52	188
0.06	42693.12	32019.84	220
0.065	48696.84	34688.16	260
0.07	56034.72	37356.48	300
0.075	64039.68	40024.8	350
0.08	73378.8	42693.12	400

Gas hold-up

Gas hold-up study is important in scaling of bubble column[12]. The gas hold-up was calculated for various air flow rates by differential pressure method. Fig. 4 shows the variation of gas hold-up with air flow rate for fixed and movable conditions of PSRBC sparger with static liquid of 1100 mm height. In both the cases the gas hold-up value increases as the flow rate

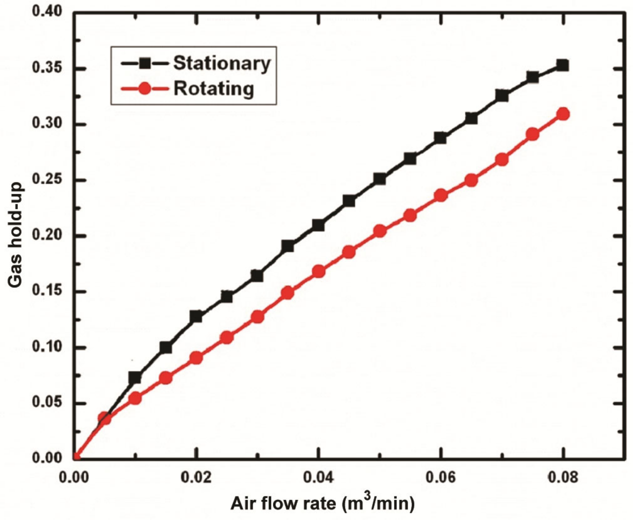


Fig. 4 — Comparison of gas hold-up with air flow rate for static and rotating PSRBC

increases. The steady growth of gas hold-up can be observed in case of rotating PSRBC due to uniform distribution and less coalescence of bubbles as compared with that of stationary PSRBC sparger. Gas hold-up is linearly varying with air flow rate for rotating PSRBC sparger within present experimental range of investigation. For a particular air flow rate (≥ 0.01 m^3/min), the εgr is lower than εgs due to a part of total energy of air is used for the rotation of PSRBC sparger. As bubbles were moving upward the probability of coalescence of bubble were less compared to stationary sparger, due to their individual existence in liquid.

Predictions of gas hold-up

The gas hold-up for the PSRBC sparger equations developed for static and rotating conditions are as;

$$\epsilon_{gS} = 0.0571 u_g^{0.8} \quad \ldots(4)$$

$$\epsilon_{gR} = 0.0571 u_g \quad \ldots(5)$$

The Eqs (4) and (5) developed for rotating PSRBC sparger have a good agreement with experimental values. The coefficients of correlation are more than 0.998, which are shown in Fig. 5.

Flow regimes

Study of flow regime gives an idea of interfacial area available for chemical process or operation in a bubble column. The flow regimes in bubble column are mainly classified as homogenous, transition and heterogeneous[2]. The "bubble swarm velocity method ($u_{sw} = u_{su}/\varepsilon_g$)" was used for flow regime identification in the present investigation[2]. The flow regime in a semi-batch PSRBC bubble column is presented in Fig. 6. The slope of the plot in Fig. 6 changes as regime transformation occurs, which is a good agreement for flow classification corresponding to visual observation (Fig. 7). It is clear that the homogenous regime existence range in case of rotating PSRBC is more than that of stationary PSRBC, as the swarm velocity is more.

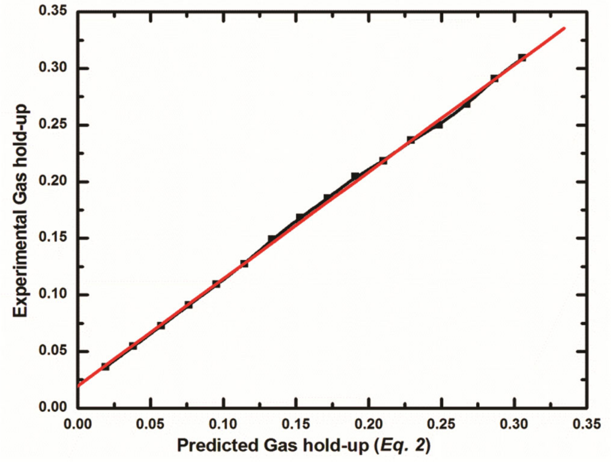


Fig. 5 — Comparison of experimental and predicted gas hold-up

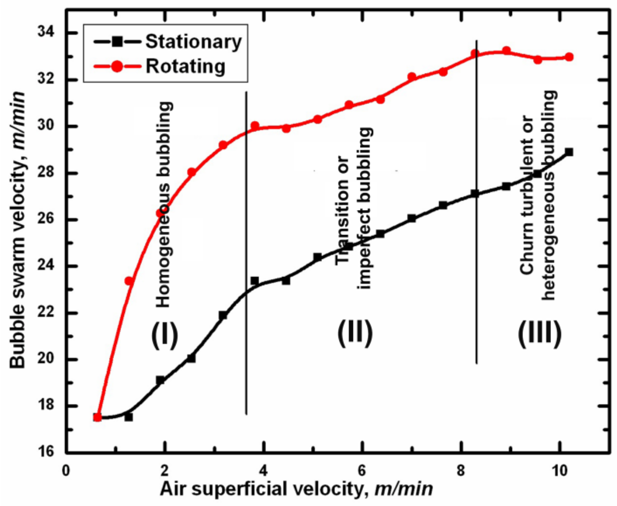


Fig. 6 — Flow regime in semi batch bubble column

Dry and Wet-run of PSRBC Sparger

The RPM and total pressure drop are two major important parameters for designing the PSRBC bubble column. Intensity of mixing increases as RPM of stirrer increases so as in case of PSRBC sparger. In static sparger a part of total energy is converted to kinetic energy, which normally increases the gas

Fig. 7 — Pictorial view of Flow regime in semi batch bubble column

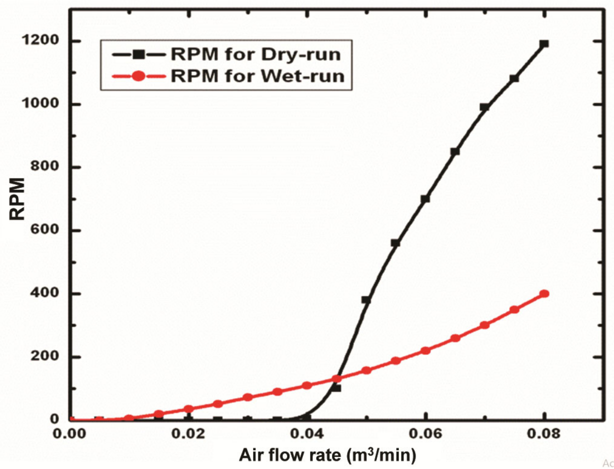


Fig. 8 — Comparison of RPM with air flow rate for dry-run and wet-run of PSRBC

velocity. In case of PSRBC sparger a part of kinetic energy is converted to rotational energy due to its unique design (angular nozzle). The gas velocity was less as compared to stationary sparger in case of rotating PSRBC sparger, which ultimately increased the regime transformation time.

Dry-run RPM

As the initiation of rotation of a PSRBC sparger depends upon its weight, the minimum air flow rate required approximately is 0.04 m^3/min. The RPM with air flow rates is shown in Fig. 8.

The developed equation for RPM_{dry} is expressed as

$$RPM_{dry} = lnQ_g + 5700 \qquad \ldots(6)$$

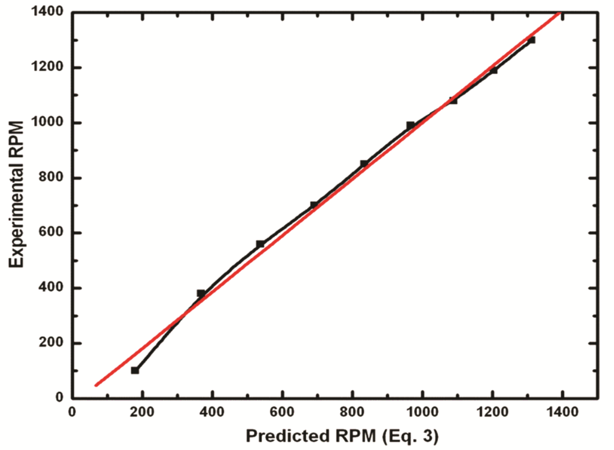


Fig. 9 — Comparison of predicted and experimental RPM for PSRBC dry-run

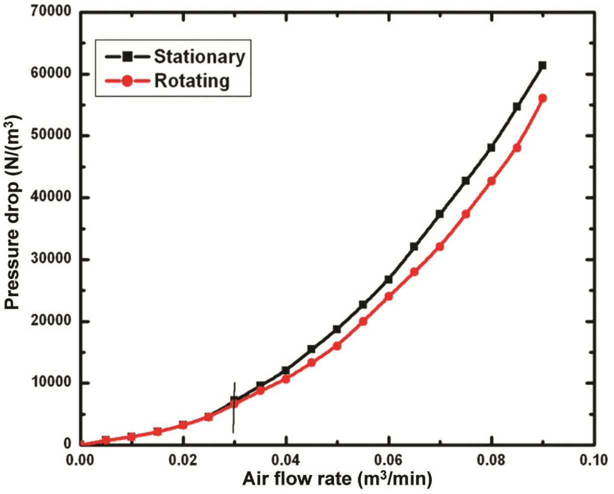


Fig. 10 — Variation in pressure drop with air flow rate between static and rotational conditions of PSRBC sparger

Fig. 9 shows the comparison of experimental and predicted RPM for the dry run of PSRBC. The developed correlation has a coefficient of correlation more than 0.99.

Dry-run pressure drop

As the combined opening area (76.34 mm^2) of the angular nozzles was more than the inlet supply area (12.56 mm^2), the total pressure-drop up to a particular air flow rate (≈0.035 m^3/min) was same for stationary and rotating PSRBC sparger. The variation in total pressure- drop with air flow rate, comparing stationary and rotating PSRBC sparger is shown in Fig. 10. After the initiation of rotation, the pressure drop is less as compared to stationary sparger due to lower flow rate of air in the angular nozzles, since the part of kinetic energy is utilized for rotation of

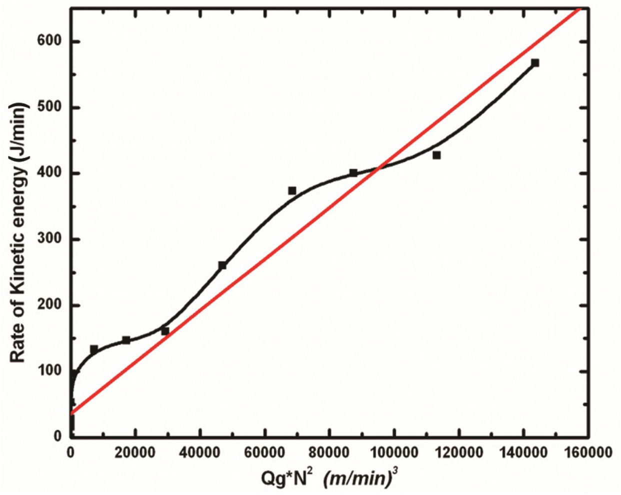


Fig. 11 — Graph for rate of rotational energy with Qg*N^2 for dry-run

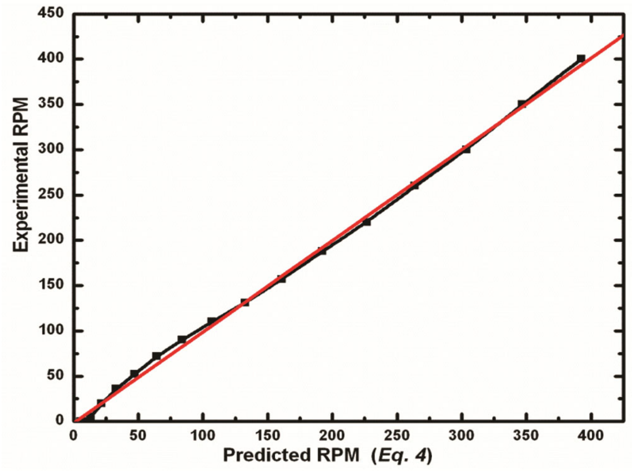


Fig. 12 — Comparison of predicted and experimental RPM for PSRBC wet-run

PSRBC. Fig. 11 shows the rate of rotational energy developed with respect to “Qg×N^2”. The constant of proportionality “Ø” is found to be as 0.004 for air-air system.

Wet-run RPM

As the bubble column was filled with water, the buoyancy force acting upward on the PSRBC sparger. The initiation of PSRBC sparger rotation started at a lower flow rate of air (≈0.02 m^3/min) compared to the dry run (≈0.04 m^3/min, Fig. 8). The variation of RPM with air flow rate is shown in Fig. 8. The RPM for a particular air flow rate was much lesser than that of in dry-run, due to the influence of fluid properties like density, viscosity etc. The developed quadratic equation for RPM$_{wet}$ is expressed as

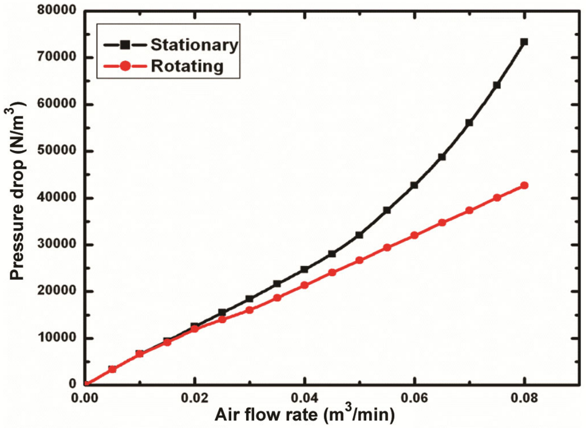


Fig. 13 — Comparison of pressure drop at various air flow rates

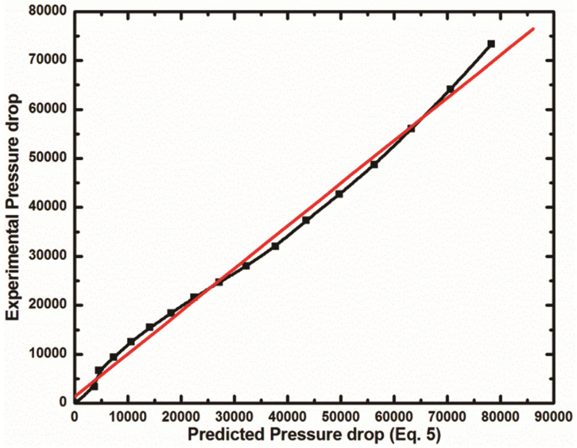


Fig. 14 — Comparison of predicted and experimental pressure drop for static PSRBC in dry-run

$$RPM_{wet} = 57518Q_g^2 + 240Q_g + 5.26 \quad \ldots(7)$$

The experimental and predicted RPM are compared in Fig. 12, and the coefficient of correlation is more than 0.998 for the developed correlation (Eq. 7).

Wet-run Pressure drop

In wet run the pressure drop increases for rotating PSRBC sparger with increase in air flow rate at a slower rate compared to static one. This is due to a part of total energy is utilized to rotate the PSRBC sparger. A pressure drop comparison plot is shown in Fig. 13. The developed pressure-drop equations for PSRBC sparger in static and rotation are as

$$\Delta P_{sta} = 7.5 \times 10^6 Q_g^2 + 379020Q_g \quad \ldots(8)$$

$$\Delta P_{rot} = 5.357 \times 10^6 Q_g \quad \ldots(9)$$

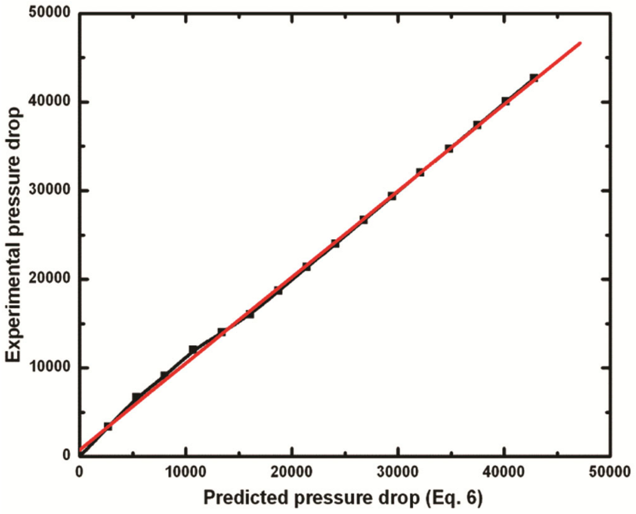


Fig. 15 — Comparison of predicted and experimental pressure drop for static PSRBC in wet-run

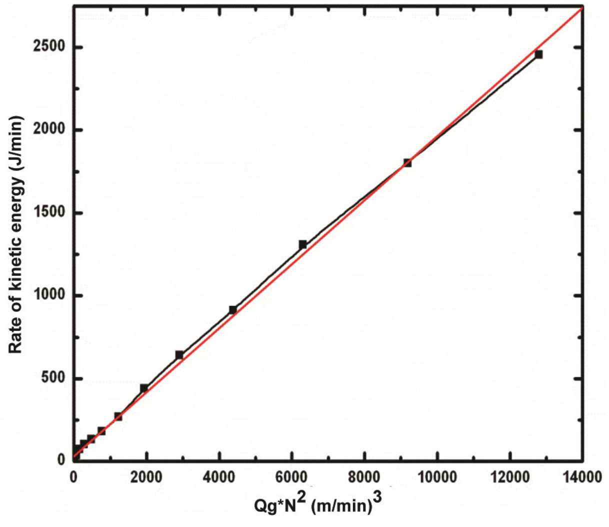


Fig. 16 — Graph for rate of rotational energy with Qg^*N^2 for wet-run

The experimental and predicted pressure drops for both the conditions of PSRBC are presented in Fig. 14 and 15, respectively. The coefficients of correlations are found to be more than 0.99 in each case. The rate of rotational energy increased as air flow rate increased, which in turn increase the rotation of PSRBC sparger. Fig. 16 shows the rate of kinetic energy developed with respect to "$Qg \times N^2$". The constant of proportionality "Ø" is found to be as 0.2 for air-water system.

Conclusion

In the present work, the design parameters of semi batch bubble column like gas hold-up, RPM and pressure-drop studies have been carried out with PSRBC sparger. PSRBC sparger has been used because it can generate bubbles with additional mixing through its rotation, which increased the interaction between the gas and liquid mediums. Swarm velocity method was used to determine the flow regimes. These regimes get established in the order of increasing gas velocity such as homogeneous bubbling regime, transition regime or imperfect bubbling and churn-turbulent regime as in case of stationary sparger. The gas hold-up increased with increase in air velocity in all the three regimes with a constant rate in contrast to the decreasing rate in stationary sparger. The constant of proportionality for "rotational energy and RPM of PSRBC relation", is found to be 0.004 and 0.2 for air-air and air-water system, respectively. It can be concluded that the fluid properties are also influencing the rotation of PSRBC sparger. The RPM, gas hold-up and Pressure drop correlations have been developed with coefficient of correlations more than 0.97, ensuring their validity over the range of experiment. The present investigation may find useful in gas-liquid system, where gas phase is supplied through bubbling manner like wastewater treatment, deaerator in power plant etc.

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