*Polish Journal of Chemical Technology, 17, **3**, 118 — 123, 10.1515/pjct-2015-0059*

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Hydrodynamics of Pilot Plant Scale Airlift Reactor in Presence of Alcohols

Somnath Nandi*, Someshwar J. Jaju[1]

Maharashtra Institute of Technology, Department of Petroleum and Petrochemical Engineering, Paud Road, Kothrud, Pune – 411 038, India
[1]Presently in Department of Chemical Engineering, Indian Institute of Science, Bangalore – 560 012, India
**Corresponding author: somnath.nandi@mitpune.edu.in*

The overall gas hold-up of a pilot plant scale internal loop airlift reactor was studied in presence of different alcohols in varied concentration. It has been observed that these simple alcohols can enhance overall gas hold-up of the airlift assembly possibly due to formation of protective thin layer over smaller gas bubbles thereby reducing chance of their coalescence. As the alcohols can be used as food source for the micro organisms present in the system, this green and environment friendly process have potential to replace usage of hazardous surfactants often used for enhancing overall hold-up in order to obtain desired mass transfer characteristics. An empirical relationship encompassing overall gas hold-up of the reactor as a function of superficial gas velocity and alcohol concentration is also developed.

Keywords: airlift reactor, hydrodynamics, gas hold-up, bubble, multiphase flow, surfactant.

INTRODUCTION

Airlift reactor is an important multiphase reactor used now-a-days for various chemical and bio-chemical processes. It finds major applications in the pharmaceutical industries and wastewater treatment utilities[1–4]. Specifically, airlift reactors are extensively used for mammalian cell cultures, biological processes with solid biocatalysts, to obtain proteins etc. from fragile cells[2, 4, 5]. Airlift reactor can be considered as modified bubble column reactor, gaining importance due to their simple design, absence of moving parts, low power requirements, lower risk of contamination and low shear stresses[5]. Airlift reactors comprises of two cylindrical (or square as the case may be) vessels called riser and downcomer respectively. Air is sparged through the riser column which causes upward movement of the fluid mass due to lowered density of dispersed phase; subsequently liquid along with some amount of gases comes down through the downcomer region. Most of the gases apart from fine and small bubbles leave continuously from an upper-zone of the airlift reactor termed as disengaging region. Airlift reactors can broadly be classified as internal-loop or an external-loop based on whether liquid circulation is done internally within a single vessel or through an attached external loop.

Gas hold-up, liquid circulation velocity and mass transfer coefficients are the key parameters affecting performance of an airlift system. Design parameters namely, diameter to height ratio, diameter of riser to that of downcomer, sparger geometry etc. also affect mixing time and mass transfer characteristics of the system. Gas hold up of the reactor is the most important parameter as it affects liquid circulation velocity, and hence the extent and degree of mixing are also affected. The overall mass transfer coefficient of the airlift assembly also depends on overall gas hold-up of the system. Overall gas hold-up of a particular airlift geometry can be varied based on operating parameters namely gas flow-rate, liquid column height etc.[6, 7].

In this research, a systematic study of overall gas hold-up in an indigenously designed internal loop airlift reactor was conducted. The effect of superficial gas velocity on overall hold-up was studied thoroughly. It has been observed that small concentration of simple alcohols namely methanol (CH_3OH), ethanol (C_2H_5OH), n-propanol (C_3H_7OH) and n-butanol (C_4H_9OH) can increase overall gas hold-up of the airlift assembly. As these alcohols can be synthesized naturally and can be utilized as food for the microbes, this green and environment friendly process have potential to replace usage of hazardous surfactants often used for enhancing overall hold-up in order to obtain desired mass transfer characteristics. Based on experimental data, a generalized correlation is developed using nonlinear regression analysis to predict overall gas hold-up based on superficial gas velocity and concentration of the organic alcohol solution. The unique model predicts gas hold-up of the airlift assembly operating with dilute solutions of various simple alcohols.

EXPERIMENTAL

Material

Different alcohols used for the study, namely, methanol (99.2%, density = 789 kg/m^3), ethanol (97.5%, density = 802 kg/m^3), n-propanol (99.5%, density = 786 kg/m^3) and n-butanol (99.7%, density = 810 kg/m^3) were purchased from Merck Co. Alcohols were diluted with tap water to prepare various concentrations of solutions [0.01, 0.02, 0.03, 0.05, 0.08 and 0.1% (v/v)].

Experimental set-up

The schematic diagram of the internal loop airlift reactor is shown in Figure 1. The pilot plant scale reactor was constructed of a 0.18 m inner diameter borosilicate glass column with 2 m in height. The draft tube was of inner diameter 0.1 m and 1.5 m in height also made up of borosilicate glass with wall thickness of 0.002 m. Therefore cross-sectional area of the draft tube acting as riser is 7.854 × 10^{-3} m^2. The draft tube was placed at 0.15 m above the bottom of the reactor. The gas sparger at the bottom has a diameter of 0.06 m containing perforations of diameter 0.001 m with a triangular pitch of 0.007 m, discussed in details in Nandi

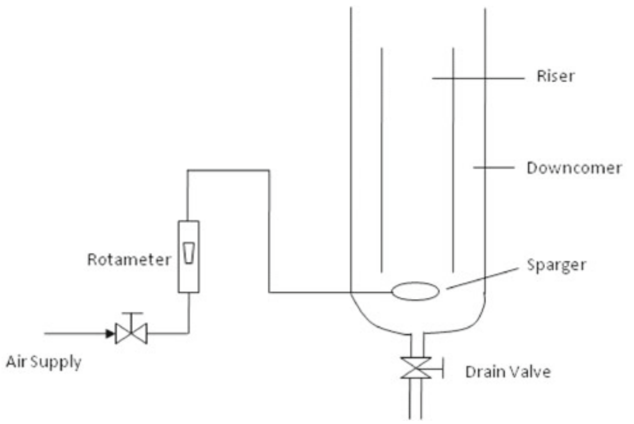

Figure 1. Schematic diagram of internal loop airlift reactor

et al. (2008)[8]. A series of experiments were performed by varying the flow rate of gas monitored through calibrated rotameter with help of precisely controlled valve in the range of 1×10^{-4} – 7×10^{-4} m^3/s. The superficial gas velocity obtained was in the range of 0.01 – 0.09 m/s. Air and water (or dilute alcohol soln.) were used as gas and liquid phases. Static liquid height was 1.74 m from bottom of airlift assembly except for the n-propanol and n-butanol solutions at 0.1% concentration when static liquid height was maintained at 1.68 m (the height was lowered to accommodate increase in overall hold-up of the system). All the design parameters of the designed airlift reactor are provided in Table 1.

Methods

Overall gas hold-up of airlift reactor was determined by the volume expansion technique of Heijnen et al. (1997)[9] measured by the graduation marked on the wall of the reactor. The aerated dispersion height without foam was used for calculating the overall gas hold-up using following equation:

$$\varepsilon = \frac{h_{disp} - h_{liq}}{h_{liq}} \quad (1)$$

where, ε denotes overall hold-up of gas in the reactor, h_{liq} represents height of the initial liquid pool without introduction of any gas and h_{disp} is the final height obtained when gas (air for our experimentation) at constant flow-rate is bubbled continuously through the sparger placed at the bottom of the reactor. Each experimental runs were repeated four times for reproducibility of data and the average values of final heights were used for calculating overall hold-up (ε) through equation (1). The physical properties of fluids under study are represented in Table 2.

Table 1. Design parameters of airlift assembly

Parameters	VALUE
Overall Volume of ALR assembly, V_{ALR} [m^3]	43.746×10^{-3}
Volume of Riser V_r [m^3]	11.781×10^{-3}
Volume of Downcomer V_d [m^3]	25.905×10^{-3}
Volume of Bottom Section V_b [m^3]	3.817×10^{-3}
Volume of Top Section V_t [m^3]	1.7804×10^{-3}

Table 2. Properties of fluids under study

Fluid	Concentration [v/v]	Density [kg/m^3]	Surface Tension [10^{-3} N/m]
Tap Water	100%	998.0	72.6
Methanol (CH_3OH) soln.	0.01%	998.0	72.4
	0.02%	998.0	72.4
	0.03%	997.8	72.3
	0.05%	997.7	72.2
	0.08%	997.6	72.1
	0.1%	997.6	72.1
Pure Methanol (CH_3OH)	100%	789	22.9
Ethanol (C_2H_5OH) soln.	0.01%	998.0	72.4
	0.02%	998.0	72.4
	0.03%	998.0	72.3
	0.05%	997.9	72.3
	0.08%	997.7	72.2
	0.1%	997.7	72.0
Pure Ethanol (C_2H_5OH)	100%	802	22.8
n-Propanol (C_3H_7OH) soln.	0.01%	998.0	72.3
	0.02%	998.0	72.3
	0.03%	997.9	72.1
	0.05%	997.9	71.0
	0.08%	997.8	71.9
	0.1%	997.6	71.8
Pure n-Propanol (C_3H_7OH)	100%	786	23.7
n-Butanol (C_4H_9OH) soln.	0.01%	998.0	72.1
	0.02%	998.0	72.0
	0.03%	997.9	71.8
	0.05%	997.9	71.6
	0.08%	997.8	71.7
	0.1%	997.8	71.6
Pure n-Butanol (C_4H_9OH)	100%	810	24.2

RESULTS AND DISCUSSION

The overall gas hold-up is the most important hydrodynamic parameter which affects liquid circulation velocity as well as overall mass transfer coefficient of the airlift reactor. Hence primary focus of the research is to measure the overall gas hold-up of the internal loop airlift reactor with variation of superficial gas velocities and a systematic study of the effect of various simple alcohols on the reactor hydrodynamics.

Figure 2 represents the variation of overall gas hold--up as the superficial gas velocity is keep on increasing for simple air-water system (with initial liquid level of 1.74 m). As shown in the figure, gas hold-up remains low till superficial gas velocity of 0.045 m/s, this lower range is mainly due to escape of most of the gas bubbles from disengaging section (Regime – 1). As superficial velocities are increased progressively (in the range of 0.045–0.08 m/s), overall gas hold-up started rising at enhanced rate due to movement of some smaller bubbles into the downcomer region, in this region liquid velocity in downcomer becomes practically equal to the bubble swarm rise velocity and we can notice stagnant bubble slug in the downcomer (Regime – 2). Enhancement of overall gas hold-up is due to entrapment of gas bubbles in downcomer region. Subsequently, as superficial gas velocity is increased to a higher range (more than 0.08 m/s for air-water system), liquid velocity in the downcomer is sufficient enough to cause recirculation of gas bubbles (Regime – 3). Only smaller bubbles will be able to dragged down from disengaging section to the downcomer, there is not much change in overall gas hold-up of the system. The observation reported here is in accordance to that of earlier reported by Blazej et al. (2004)[6].

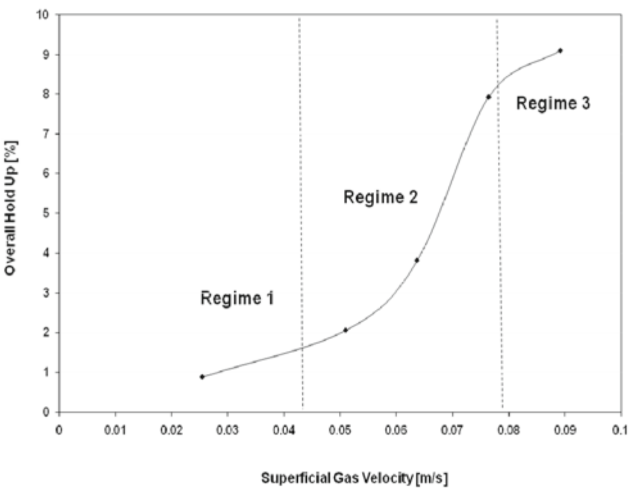

Figure 2. Variation of overall gas hold-up of airlift reactor based on superficial gas velocity. Regime – 1 indicates gas is not present in the downcomer and most of the gases entered leave from disengaging section on the top, Regime – 2 highlights stratification and stagnation of gas bubbles in the downcomer whereas Regime – 3 represents complete bubble recirculation throughout the riser and downcomer region

Detergent solutions of different concentration were used as liquid medium to study effect of surfactant on hold-up characteristics of airlift reactor. Dilute aqueous solutions of surfactants; represent a coalescence inhibiting system, influences global hydrodynamics as it affects bubble size. The active ingredient of alkyl ethoxylate sulfate has a polar and non-polar end, when dissolved in water, the polar ends tend to adsorb at gas-liquid interface and may accumulate around bubbles thus forming a protective monolayer over the bubble which inhibits coalescence between two adjacent bubbles. On movement of a bubble through pool of liquid, adsorbed molecules are pushed back to the bubbles causing surface tension gradient, which opposes the tangential shear stress. Consequently, the increase in drag on bubbles resulting reduction in bubble rise velocity and hence increase overall gas hold-up. As represented by the Figure 3, increase in detergent concentration increases overall hold-up, this may be due to formation of more stable monolayer over the bubbles and hence reducing the chance of their coalescence.

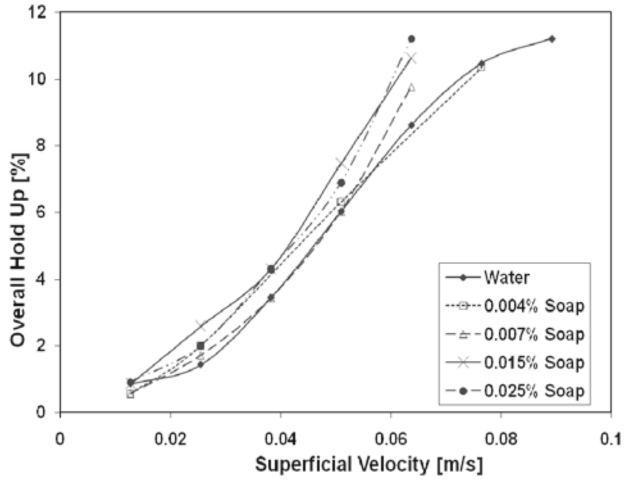

Figure 3. Variation of overall gas hold-up (ε) of airlift reactor as function of superficial gas velocity (U_g) for various concentrations of detergent solutions

To make the process green and environment friendly, different simple alcohols namely methanol (CH_3OH), ethanol (C_2H_5OH), n-propanol (C_3H_7OH) and n-butanol (C_4H_9OH) were tried and their effect was studied on airlift hydrodynamics. As evident from the Figure 4, these alcohols increases the overall gas hold-up of the reactor

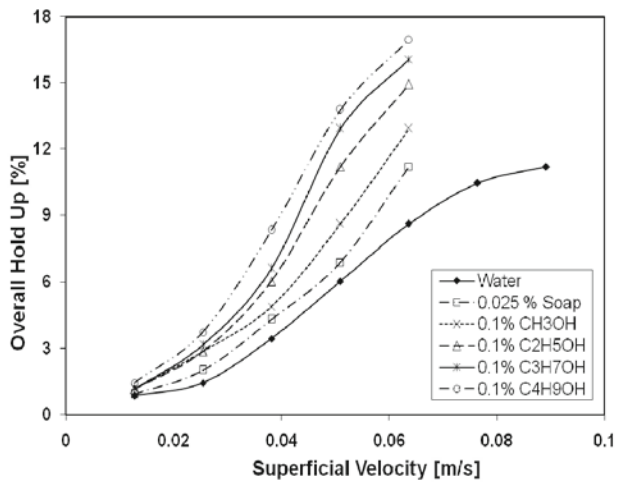

Figure 4. Performance of simple organic alcohols in comparison to detergent solution to enhance overall gas hold-up (ε) of airlift reactor

may be due to formation of protective monolayer over the colliding gas bubbles. As one move towards higher aliphatic alcohols, chance of formation of protective layer increases due to increase in carbon chain-length. The plausible mechanism may be that n-butanol can able to form a much stable protective layer compared to smallest methanol where polar and non-polar ends are very nearby. Such observation is clearly in accordance with the earlier published results of Moraveji et al. (2011)[10].

The results encouraged to study the effect of various organic alcohols on airlift reactor hydrodynamics, and the effect of simple aliphatic alcohols namely methanol, ethanol, n-propanol and n-butanol at different dilution (0.01, 0.02, 0.03, 0.05, 0.08 and 0.1%) on overall gas hold-up of the system were studied thoroughly. The results obtained are represented by Figure 5 (a–d) for the alcohols in the order of increased chain length. As evident from all of these plots, increase in concentration of alcohol increases the overall gas hold-up, possibly for better coverage of the colliding gas bubbles by providing a thin film of protective layer. As we move towards higher alcohols, hydrophobicity increases and hence protective thin layer over dispersed gas bubbles becomes more established, and it stabilizes smaller bubbles more efficiently restricting them from coalescence, causing enhanced gas hold-up. It is clear from the Figure 4 that overall gas hold-up with dilute n-butanol is almost 50% more than that of methanol solution. This result stand very encouraging as this type of simple organic alcohols can be used to enhance overall gas hold-up which in turn will lead to enhanced mass transfer coefficients essential for slow biochemical reactions. As airlift reactors are used for slow biodesulfurization (BDS) reactions[11–13] where enhancement of overall mass transfer coefficient is a challenging task, these simple alcohols may act as a boon[14]. In addition to increment of gas hold-up of the reactor, these organic alcohols can also act as food source for the microbes, thereby enhancing chance of microbial growth leading to better and efficient process development.

Various models are available to predict hydrodynamics and mass transfer characteristics[5]. Here a generalized model is developed to predict overall gas hold-up of the airlift reactor for all types of alcohols under study. It has been observed that superficial gas velocity and alcohol concentration are the most significant variables affecting the overall gas hold-up. The following generalized model is proposed for prediction of overall gas hold-up for the internal loop airlift assembly while working with various dilute alcohol solutions:

$$\varepsilon = k\ U_g^m\ C_{Alcohol}^n \qquad (2)$$

As evident from the earlier discussion, different alcohols are affecting hydrodynamics of airlift reactor to different extent; separate models are fitted for indivi-

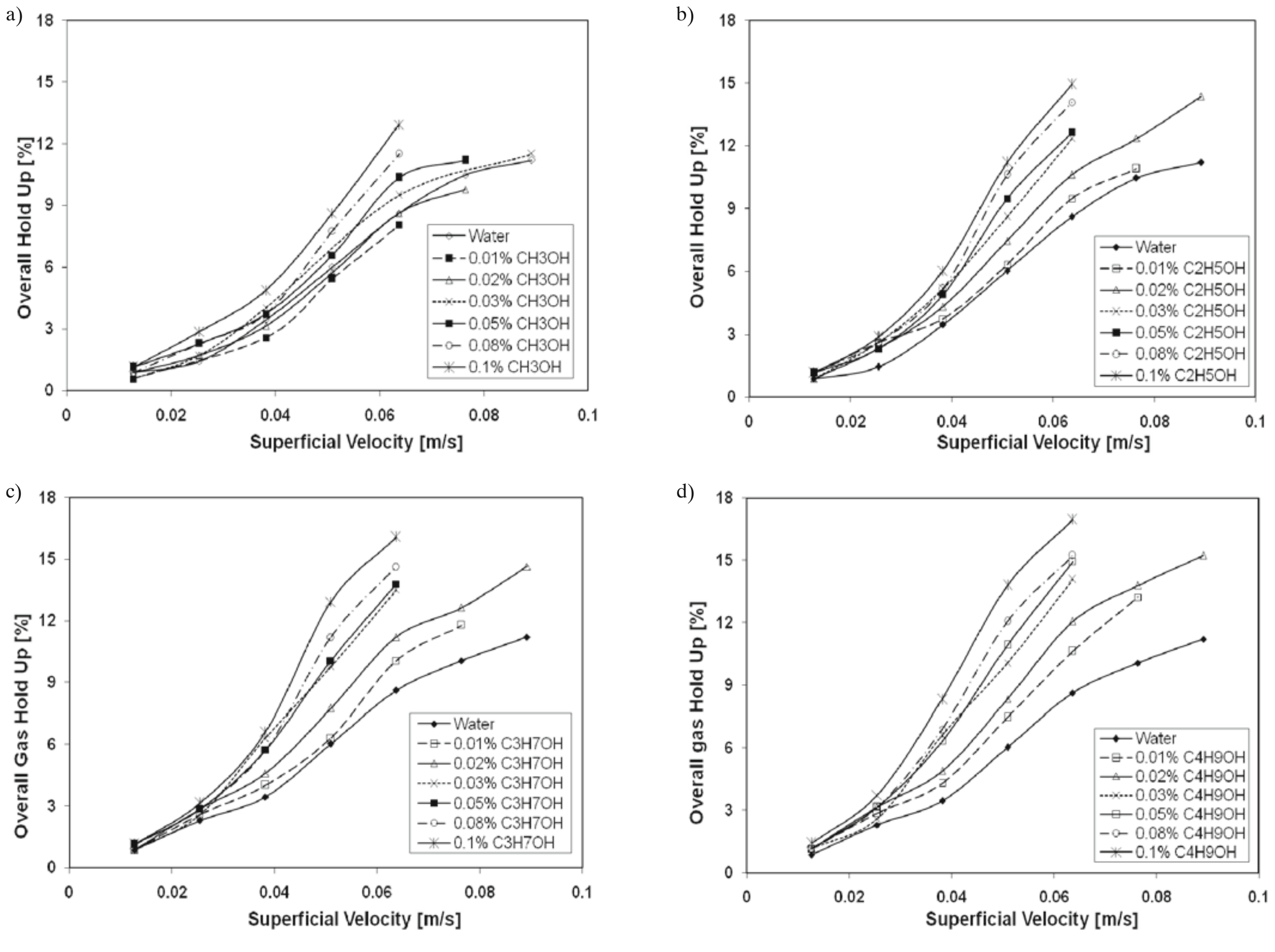

Figure 5. Overall gas hold-up (ε) of airlift reactor as function of superficial gas velocity (U_g), (a) Methanol solution in different concentrations, (b) Ethanol solution in different concentrations, (c) n-Propanol solution in different concentrations, (d) n-Butanol solution in different concentrations

dual alcohols. As there are three parameters namely coefficient k, index m and index n to be determined simultaneously, the parameter estimation exercise falls under the realm of multi-variable optimization. MATLAB software is used to obtain the best possible empirical model based on nonlinear regression analysis. It should be noted that equations of all the alcohols are following the generalized form represented through equation (2). In particular overall gas holdup for dilute methanol (CH_3OH), ethanol (C_2H_5OH), n-propanol (C_3H_7OH) and n-butanol (C_4H_9OH) are represented by equations (3)–(6) respectively as represented below.

$$\varepsilon_{CH_3OH} = 1.3962\ U_g^{1.4288}\ C_{CH_3OH}^{0.2419} \quad (3)$$

$$\varepsilon_{C_2H_5OH} = 1.6228\ U_g^{1.4959}\ C_{C_2H_5OH}^{0.2459} \quad (4)$$

$$\varepsilon_{C_3H_7OH} = 1.9707\ U_g^{1.4450}\ C_{C_3H_7OH}^{0.2566} \quad (5)$$

$$\varepsilon_{C_4H_9OH} = 2.2682\ U_g^{1.3877}\ C_{C_4H_9OH}^{0.2463} \quad (6)$$

The developed model is in good agreement with the experimental results and can efficiently predict all the trends and patterns obtained experimentally (average error of 7%). Detailed analysis of the proposed model are provided in Table 3 where the average error along with its minimum and maximum values were calculated, the standard deviation values were also reported. The performance of regression based model is evident from Figure 6, where model predicted gas hold-up is plotted as function of experimentally obtained gas hold-up. As evident from the figure, model predicts best for ethanol solution and deviation is largest for n-butanol.

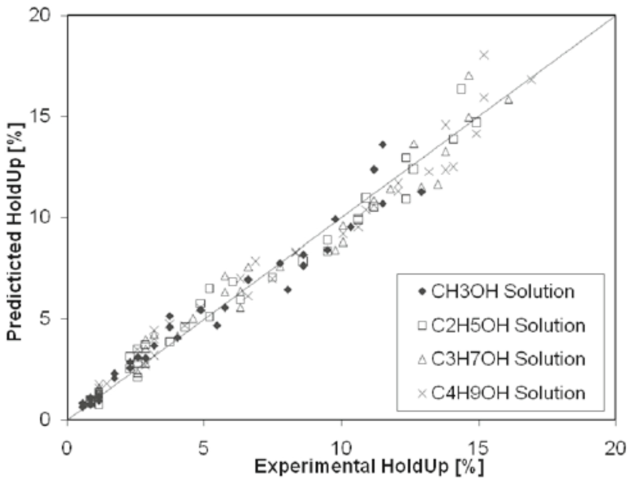

Figure 6. Developed nonlinear model predicted gas hold-up versus experimentally obtained gas hold-up for all alcohols under study

CONCLUSIONS

The study highlights possible application of organic alcohols as green surfactants. It indicates the effect of simple organic alcohols namely methanol, ethanol, n-propanol and n-butanol and their concentrations on overall gas hold-up of pilot plant scale internal loop airlift reactor. Alcohols may have formed thin film over smaller gas bubbles which caused stabilization of these bubbles – possibly due to reduction in coalescence – leading to the enhanced gas hold-up. As volumetric mass transfer increases with increase in gas hold-up for airlift reactors, these results will be of immense importance for process development of slow biochemical systems, specifically for biodesulfurization in presence of microbes as these green surfactants can be potential food for the microbial culture as well. It has been observed that as we move towards higher alcohols, overall gas hold-up increases significantly. A generalized empirical model was developed to predict overall gas hold-up based on superficial gas velocity and concentration of various alcohols under study.

ACKNOWLEDGEMENT

A research grant from Board of College and University Development – University of Pune (Ref. BCUD / 578 dated 10/01/2007) is gratefully acknowledged.

NOMENCLATURE:

$C_{Alcohol}$ – concentration of alcohol in solution [v/v]
h_{disp} – final dispersed height of gas – liquid mixture inside airlift reactor [m]
h_{liq} – height of the degassed liquid column in airlift reactor [m]
U_g – superficial gas velocity [m/s]

Greek symbols

ε – overall gas hold-up in the airlift reactor [–]

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Table 3. Detailed analysis of the accuracy of the model proposed for various dilute solutions of alcohol

Alcohol Used	Average Error [%]	Minimum Value of Error [%]	Maximum Value of Error [%]	Standard Deviation
Dilute solution of Methanol	6.49	0.06	47.00	17.01
Dilute solution of Ethanol	3.43	0.15	36.77	15.20
Dilute solution of n-Propanol	6.92	0.51	38.56	15.60
Dilute solution of n-Butanol	6.91	0.24	48.22	16.56

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