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Analysis of Foaming Flow Instabilities for Dynamic Liquid Saturation in Trickle Bed Reactor

Vijay Sodhi and Ajay Bansal

Abstract**—**The effects of different parameters on the hydrodynamics of trickle bed reactors were discussed for Newtonian and non-Newtonian foaming systems. The varying parameters are varying liquid velocities, gas flow velocities and surface tension. The range for gas velocity is particularly large, thanks to the use of dense gas to simulate very high pressure conditions. This data bank has been used to compare the prediction accuracy of the different trendlines and transition points from the literature. More than 240 experimental points for the trickle flow (GCF) and foaming pulsing flow (PF/FPF) regime were obtained for present study. Hydrodynamic characteristics involving dynamic liquid saturation significantly influenced by gas and liquid flow rates. For 15 and 30 ppm air-aqueous surfactant solutions, dynamic liquid saturation decreases with higher liquid and gas flow rates considerably in high interaction regime. With decrease in surface tension i.e. for 45 and 60 ppm air-aqueous surfactant systems, effect was more pronounced with decreases dynamic liquid saturation very sharply during regime transition significantly at both low liquid and gas flow rates.

Keywords**—**Trickle Bed Reactor, Dynamic Liquid Saturation, Foaming, Flow Regime Transition

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I. INTRODUCTION

THE arrival time of a space probe traveling to Saturn can be predicted more accurately than the behavior of a fluidized bed chemical reactor. Even though the above quotation by Geldart [1] is almost 24 years old it remains true in the new millennium of fluidization engineering. Trickle bed reactors are randomly packed columns in which reactant-carrying gas and liquid phases flow co-currently downwards. They are widely used in the petroleum industry such as in hydrotreating and hydrocracking processes. In petroleum industry, foaming plays an important role in petroleum recovery processing and productivity. Conventionally most of the industries rely on frequently used gas continuous flow (GCF) where operational output is satisfactory but not efficient as compare to pulsing flow (PF) and foaming pulsing flow (FPF) [2]. These three phase reactors (reactions) are widely used in industrial practice of treatment of foaming petroleum products [3], [4]. Foams play an important role in productivity and petroleum recovery and processing [5]. In actual practice foam formation is inhibited by adding antifoaming agents or defoamers, this may increases overall production cost.

Knowledge of liquid hold-up is key function in reactor design modeling and reaction performances. For high heat generated during exothermic, liquid hold-up controls and enables the better wetting efficiency and prevents the hot spot formation. Liquid holdup and two-phase pressure drop are the two basic hydrodynamic parameters that are often inter-linked with reaction conversion and selectivity, power consumption and interfacial mass transfer that take place in a trickle-bed reactor. Experimental evidence of liquid saturation for foaming liquids was first presented by [6]. Further, Schwartz [7] showed that, when the pores of the particles are filled by capillarity, external liquid holdup for the porous packing is sufficiently close to the total liquid holdup for the nonporous packing. Liquid holdup has a direct influence on residence time, mass transfer, heat transfer, wetting efficiency and pressure drop in trickle-bed reactors. The existence of multiple hydrodynamic states to various non uniform flow rates of gas and liquid showed pulsing due to strong interaction of gas and liquid [8].

The most common techniques to estimate experimental liquid hold-up are drainage, weighing and liquid-phase tracing. In case of nonporous packing material, the drainage technique consists of shutting off simultaneously the gas and the liquid input and collecting the liquid at the bottom of the bed. Based on Holub's slit model [9], the dependence of liquid

TABLE I
UNITS FOR PHYSIOCHEMICAL PROPERTIES

Symbol	Quantity	SI Units
a_L	specific liquid-gas interfacial area per volume reactor	mm
d_p	effective particle diameter	mm
Re	Reynolds Number	Dimensionless
g	acceleration due to gravity	
G	gas superficial velocity	Kg/m^2s
L	liquid superficial mass	Kg/m^2s
ΔP	two-phase pressure drop	N/m^2
ΔP_G	pressure drop based on gas	N/m^2
ΔP_L	pressure drop based on liquid	N/m^2
E_1, E_2	constnts of the Ergun equation for single phase flow on the packing of interest	Dimensionless
σ		N/m
ρ_W	liquid phase surface tension	Kg/m^3
ρ_L	density of liquid	Kg/m^3
μ_L	density of water	Kg/m.s
μ_W	viscosity of liquid,	Kg/m.s
ε	viscosity of water	Dimensionless
β_{exp}	bed void fraction	Dimensionless
	Dynamic liquid saturation	

[a]Gaussian units are m = meter, kg = kilogram, mm = millimeter, N = Newton, s = seconds

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holdup on pressure drop is widely influenced by ε_L:

$$\varepsilon_L = \varepsilon_B \left(\frac{E_1 \mathrm{Re}_L + E_2 \mathrm{Re}_L^{\ 2}}{Ga_L \{1 + [(\Delta P / Z) / \rho_L g]\}} \right)^{1/3} \quad (1)$$

$$Re_L = \frac{d_p L}{\mu_L (1-\varepsilon) \alpha_w} \quad (2)$$

Parameters characterization for both GCF and PF are different for both Newtonian and non Newtonian fluids. Further, Grandjean [10] has shown that the gas flow has a considerable influence on the hydrodynamics of TBR. Especially at high operating pressure and the interactions between the gas and liquid phases are not negligence with regard to the momentum transfer mechanisms. Bartelmus [11] predicted that, for identical flow conditions, the dynamic liquid saturation can vary up to 15% which is accompanied by a significant variation of pressure drop. Larachi [12] presented different correlation in terms of Lockhart-Martinelli parameters, flow variables and packing characteristics. All of observed models performed almost equally well and can be recommended distinguish in liquid holdup predictions [13]. Liquid holdup and two-phase pressure drop are the two basic hydrodynamic parameters that are often inter-linked with reaction conversion and selectivity, power consumption and interfacial mass transfer that take place in a trickle-bed reactor [14]. The disadvantage of any empirical correlation is that the pertinent equations hold only for the specific packing materials. However, liquid holdup may be reduced, and consequently overestimated by the correlations proposed in the literature.The systems on which work has been already done experimentally, would enables to prior information to those fluids display foaming and aims significantly to what type of systems must need further researches. Therefore several attempts done to solve this problem, found in literature are listed below in Table: II. These authors reported that the values of two-phase pressure drop for foaming systems are much lower than those prevailing with non-foaming systems of close physicochemical properties under identical flow rates of both phases.Past researches shows the dependence of decreasing surface tension with increasing foaming nature of listed systems. The Sodium Lauryl Sulphate used for present study produces a moderate to extensive foam formation ability depend upon concentration used and other parameters. Bansal [4] produced very good correlation to predict foaming/pulsing transition regime by experimentation of 6 ppm and 12 ppm Sodium Lauryl Sulphate. Therefore to consider observations of past researches in a better manner and predict a more accurate correlation, we used higher concentration of Sodium Lauryl Sulphate which also exhibits a similar physiochemical properties to chemicals listed in literature. During preliminary tests, concentrations over 60 ppm showed a very intensive foaming and resulted into blockage, clogging and

TABLE II
DESCRIPTION OF FOAMING SYSTEMS LISTED IN LITERATURE

Type of Liquid	ρ_L (Kg/m^3)	μ_L x 10^{-3} (Kg/m.s)	σ x 10^{-3} (N/m)	References
Kerosene	790.8	0.99	25.3	[15]
Cyclohexane	780.1	0.93	25	
0.5 % CMC	1001.40	17.78	54	[16]
1.0% CMC	1004.67	55.99	51.9	
59 % Ethanol	891.5	2.45	29.78	[17]
24 % Methanol	956.1	1.67	45.35	
43 % Methanol	912.7	1.67	35.90	
4 % Butanol	993	1.13	34.25	[11], [18]
56 % I-propanol	895.5	3.74	24.18	
34 % I-propanol	947.8	3.02	27.43	
60 % Glycerol	1148.0	5.93	64.53	[3], [4]
77 % Glycerol	1192.7	27.04	63.24	
6 ppm SLS*	999.5	1.13	59.10	
12 ppm SLS	999.5	1.13	55.0	
0.25 % CMC CTAB	1001.2	6.66	56.16	[14]

over flow within the reactor. Therefore present study is limited to four concentrations of 15, 30, 45 and 60 ppm aqueous solution of Sodium Lauryl Sulphate along with water have been investigated in the form of more than 240 experiments (Table 2). The impact of liquid and gas flow rates, surface tension, gas density, solution concentration and particle diameter on the transition from trickle to pulse flow analyzed by change in two phase pressure drop and liquid hold up.

II. EXPERIMENTAL SET-UP

A schematic of the experimental setup is shown in Fig. 1 and 2. The experimental section mainly consists of a packed column, the movement of phases being concurrent down flow over the spherical glass packing. Liquid was pumped from a liquid feed tank through a rotameter to the top of the column and fed to the distributor. Experiments were carried out on a 10 cm diameter glass column, packed with spherical glass beads of size 7.12 mm were provided at the top of the column. Air coming from the compressor via air surge tank was first saturated with process liquid in a saturator before introducing into the packed bed. This would avoid the effect of mass transfer between the gas and liquid phase inside the column. For the even distribution of liquid, a distributor was provided at the top of the packed section. The packing in the column was supported on a stainless steel mesh. The liquid was introduced into the column at the desired air rate. Air is drawn from compressor through pressure regulator.

Solenoid valve in the air flow is provided so as to cut the supply of air instantly for the measurement of dynamic liquid saturation, air and liquid phase after transverse the length of the packing were discharged at the bottom of the column through a conical separator/discharger. Two quick closing solenoid valve provided at the top of the column, one each in the air and liquid flow line facilitated in simultaneous cut-off the phases when desired for holdup measurement. The liquid was introduced into the column at the desired rate and column was allowed to attain the steady state. The flow pattern across

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the glass column was visually observed. For each run flow was kept constant and the flow rate was gradually increased in steps. No foam was noticed in the column at low flow rates. The dynamic liquid saturation of the system was studied by drainage method. The inlet and outlet valve of the system were closed simultaneously. The liquid was collected in the column for 30-45 minutes till formation for stable foaming/pulsing flow at high flow rates.

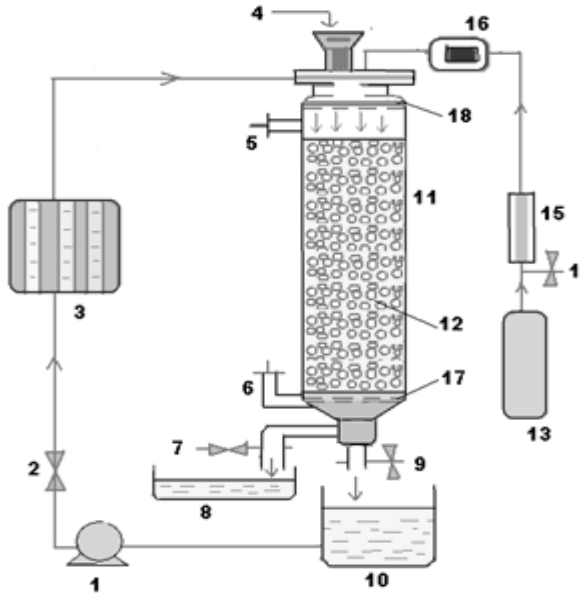

Fig. 1 Schematic representation of TBR used in present study

1 Control valve for gas stream	2 Control valve for liquid stream
3 Rotameter	4 Tracer inlet valve
5 Air exit for packed bed	6 Air out valve for trickle
7 Liquid outlet valve	8 Liquid collector for RTD
9 Drain valve for Hold-up	10 Liquid collector
11 Transparent glass column	12 Solid catalyst packing
13 Air compressor	14 Air ON/OFF valve
15 Air Saturator	16 Air flow meter
17 Mesh to control drop solid	18 Liquid distributor

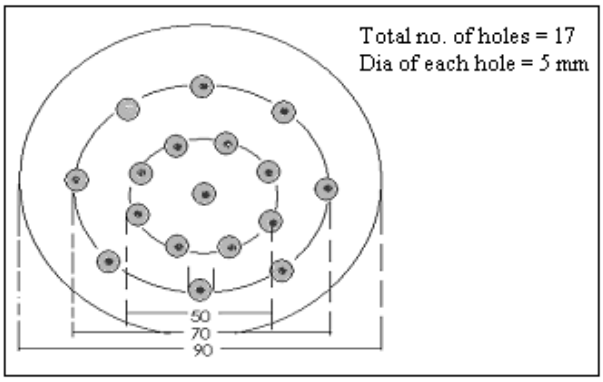

Fig. 2 Schematic of liquid distributor situated on top of column.

III. RESULTS AND OBSERVATIONS

Each set corresponds to reading at same air flow velocity whereas liquid flow rate is varied over a wide range of points in low as well as high-interaction regimes. Solid packing of 7.12 mm glass beads, air flows of 0.0512 – 0.2559 Kg/m^{2}s were used to investigate 15 ppm , 30 ppm, 45 ppm and 60 ppm Sodium Lauryl Sulphate – tap water systems. During experimentation 30 flow regime transition points were recorded amongst more than 240 experiments at various liquid flow rates. Table III presents the physiochemical description of systems used for present study.

TABLE III
PHYSIOCHEMICAL PROPERTIES OF SYSTEMS USED IN STUDY

Type of Liquid Used	ρ_L (Kg/m^3)	μ_L x 10^{-3} (Kg/m.s)	σ x 10^{-3} (N/m)
Water	997.8	1.01	70.1
15 ppm SLS *	999.1	1.13	58.3
30 ppm SLS	999.2	1.13	51.8
45 ppm SLS	999.4	1.15	47.2
60 ppm SLS	999.9	1.19	44.1

Sodium Laurel Sulphate

A. *Effect of Liquid Flow Rate*

Figure 3 showed β_{exp} or dynamic liquid saturation increases with increase in liquid flow rate in low interaction regime (GCF) then further decreased with the change in regime transition in high interaction regime. Especially after reaching transition boundary, again a gradual increase in dynamic liquid saturation persists in high interaction regime was observed. For 30 ppm surfactant - water solution showed comparatively low β_{exp} in low interaction regime (GCF) than 15 ppm surfactant – water solution. Figure 3 also shows a relation between effect of liquid flow rate and β_{exp} on packed bed reactor (without downflow air supply) produced some interesting results. A gradual increase in β_{exp} was observed in both low and high interaction regimes at corresponding liquid flow rates.

Observations of β_{exp} with change in liquid flow rate for 45 ppm and 60 ppm (Figure 4) are significantly very low as compare to 15 ppm and 30 ppm aqueous surfactant solution. Here more noticeable thing observed in investigation of air-aqueous surfactant system is, that as the regime changes from trickle flow to foaming pulsing flow, β_{exp} decreases with increase in surfactant concentration. It is clear that, for air-aqueous surfactant system instead of liquid flow rate, the effect of gas flow rate is more pronounced on liquid saturation.

Further, Figure 5 presents the comparison between the present investigation with trendlines proposed in literature data. Experimental data for present study lie higher than observations of [11], [18] was observed significantly low value of β_{exp} in both low and high interaction regimes. The trendline proposed by [15] and by [19] showed much higher

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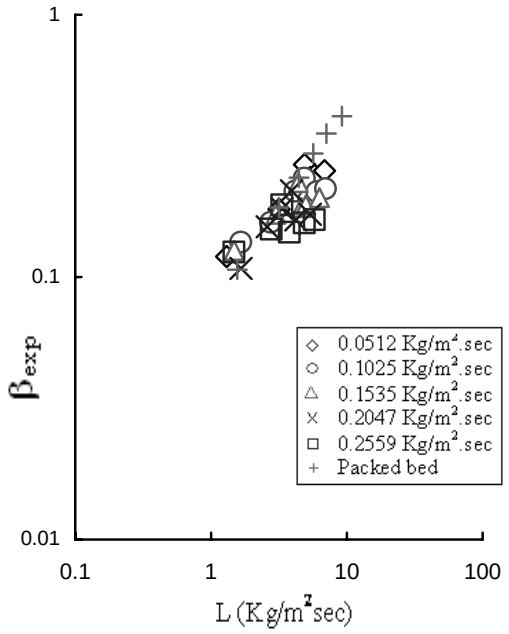

Fig. 3 Effect of liquid flow rate on liquid saturation for 30 ppm surfactant-water system

values of β_{exp} in higher interaction regime. These fluctuations in results are possibly due to impact of foam formation on different foaming systems studied in literature. Here more noticeable thing is effect of foam concentration is more prominent and significantly controls the value of dynamic liquid saturation in both trickle flow and foaming pulsing flow regime.

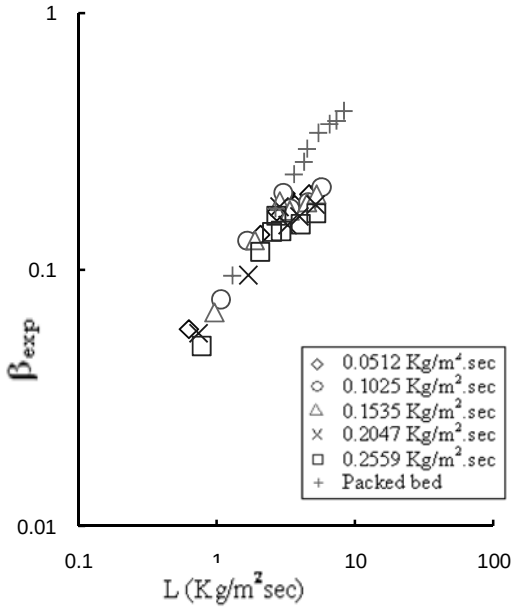

Fig. 4 Effect of liquid flow rate on liquid saturation for 60 ppm surfactant-water system

Figure 6 presents the dependence is not much similar to that observed for non-foaming air-water system (at 30º C) corresponds to low liquid and high air flow rates and vice-versa. Surprisely, results observed are completely different to the foaming systems.

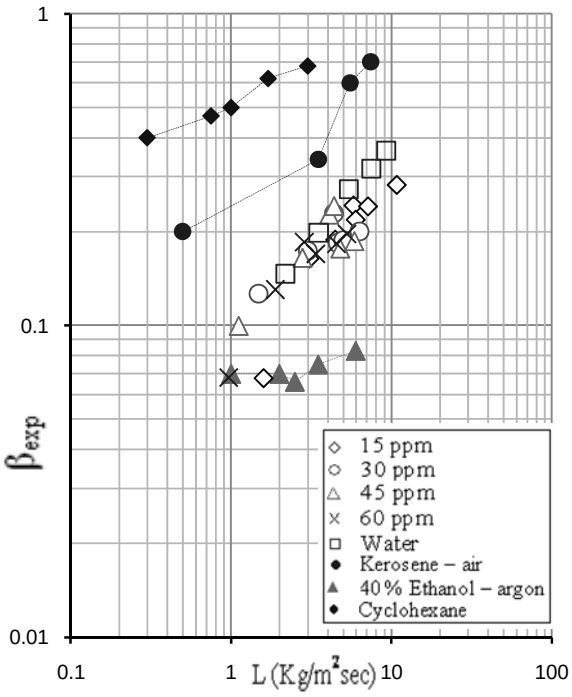

Fig. 5 The comparison of influence of liquid flow rate on β_{exp} observed during past investigations. Full points are Kerosene – air system [15]; 40% Ethanol – argon [11], [18]; Cyclohexane – air [19] all at G = 0.153 – 0.204 Kg/m^{2}s. Empty points are different concentrations of surfactant – air system for present study.

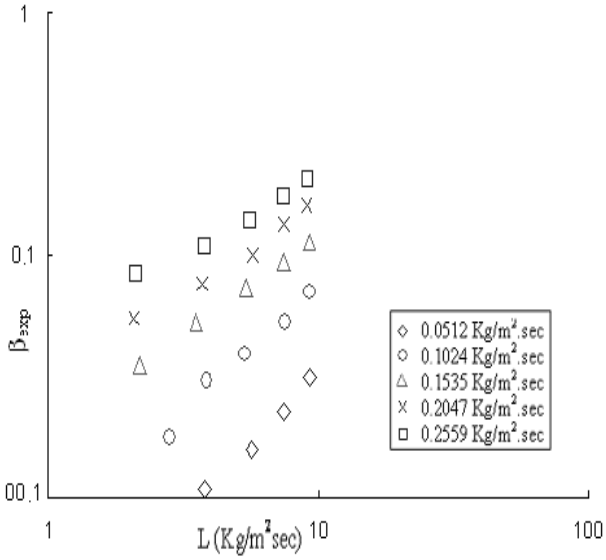

Fig. 6 Effect of liquid flow rate on dynamic liquid saturation for non-foaming water at gas flow velocities of 0.0512 – 0.2559 Kg/m^{2}s

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B. Effect of Gas Flow Rate

Figure 7 confirmed that the interaction between gas and liquid phases is small and barely affected by variations in the liquid flow rate. The fluid dynamics is liquid-gravity driven and gas-phase independent. The effect of gas flow rate of 0.0512 Kg/m^{2}s is significantly low and lead to high β_{exp} values in both low and high interaction regimes. Similar trends are observed for all concentrations of investigated systems at this gas flow rate. Figures 8 shows, at higher gas velocities, dynamic liquid saturation significantly decreases drastically as compared to other cases. The experiments revealed that the appearance of foam causes decrease in dynamic liquid saturation. The β_{exp} in the foaming pulsing flow regime is dependent significantly on the gas flow rate in

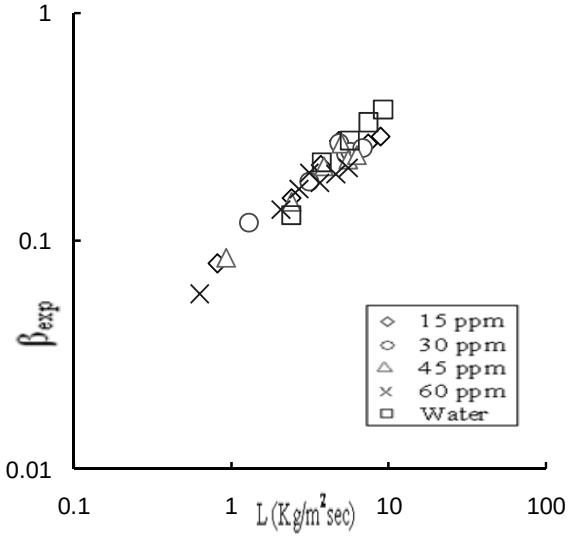

Fig. 7 Effect of gas velocity of 0.0512 Kg/m^{2}s on β_{exp} and L for non foaming water and foaming systems of surfactant

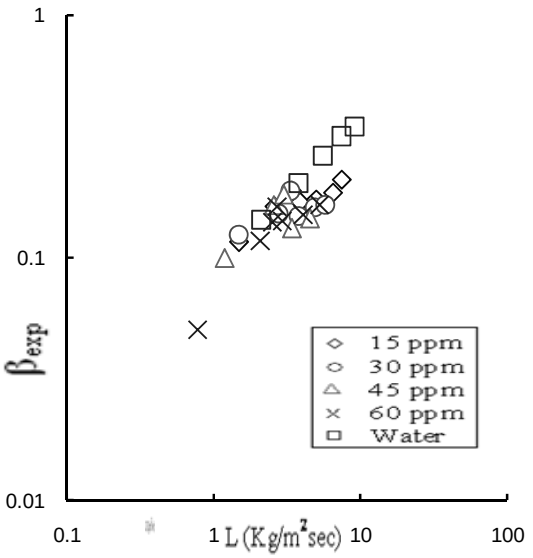

Fig. 8 Effect of gas velocity of 0.2559 Kg/m^{2}s on β_{exp} and L for non foaming water and foaming systems of surfactant

the bed. However, the increase in the gas velocity caused distinct decrease in amount of liquid hold up. In high interaction regime the interaction between gas and liquid increased dramatically and yielded the low dynamic liquid saturation.Figure 9 presents the comparison between present study and trendlines observed by [11], [18], [3], [4] and by [14] at different gas flow rates for foaming system of 40 % ethanol, 6 ppm Sodium Lauryl Sulphate and CTAB (Cetyltrimethylammoinumbromide) respectively. Figure 9 also shows the experimental data for present study lies higher than trendline observed by [11] and [18] for air-40 % ethanol system. While comparing with [3], [4] present experimental trends are exactly similar to air-6ppm surfactant system. The trends observed by [14] for air-CTAB system lies higher than present investigation. Present trends showed it is crystal clear that, the β_{exp} decreases with increase in gas flow rate and effect of change in gas flow rate is much pronounced compare to liquid flow rate in downflow packed bed reactors.

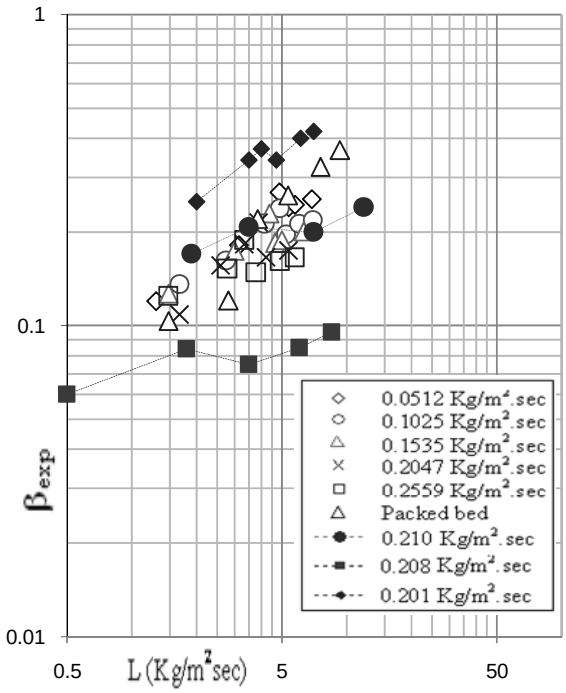

Fig. 9 Comparison of influence of gas flow velocities on β_{exp} observed for present study with literature data. Empty points are trends observed for 30 ppm surfactant-air system at different gas flow velocities. Full points are air-6 ppm surfactant system at G = 0.210 Kg/m^{2}s [3], [4]; 40 % Ethanol–argon system at G = 0.208 Kg/m^{2}s [11], [18] and air-CTAB system at G = 0.201 Kg/m^{2}s [14].

C. Effect of Surface Tension

Figures 10-12 present the influence of surface tension on dynamic liquid saturation corresponds to different gas flow rates. The solution of low surface tension produced excessive foam in foaming pulsing regime. Further in high interaction regime, effect of foam formation and low surface tension persists and resulted to decrease in β_{exp} (Figure 10). This phenomenon is much significant as β_{exp} decreases in both low

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and high interaction regimes for low surface tension solutions of 45 and 60 ppm surfactant. In high interaction regime some interesting results are observed for dynamic liquid saturation for 45 ppm and 60 ppm surfactant with least surface tension (47.4 N/m and 44.2 N/m respectively). It was observed to yield significantly low value of dynamic liquid saturation (Figure 11).

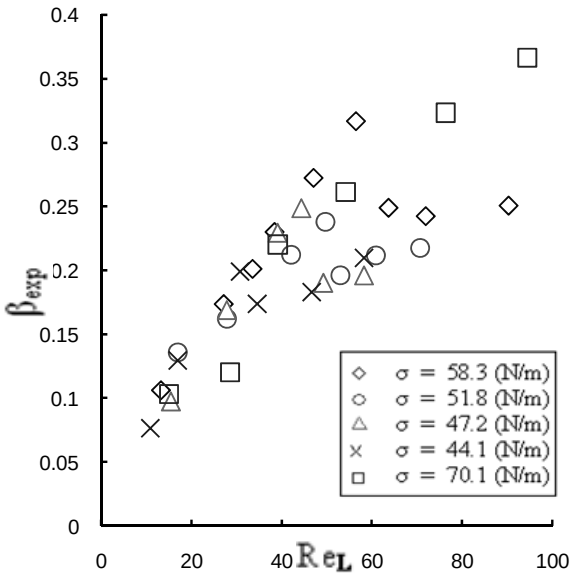

Fig. 10 Effect of surface tension on β_{exp} for non foaming water and aqueous solutions of surfactant at gas velocity of 0.1024 Kg/m^{2}s

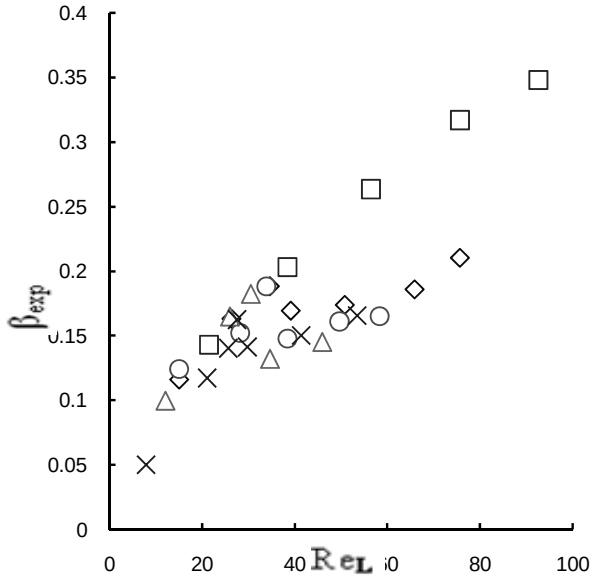

Fig. 11 Effect of surface tension on β_{exp} for non foaming water and aqueous solutions of surfactant at gas velocity of 0.2559 Kg/m^{2}s

This is possibly due to large disappearance of void of spaces those were filled with foam through out the column. The foam captured the space which was occupied by the liquid and gas just before the transition and leads to low dynamic liquid hold up after transition. For present study, foam generally starts occurred at liquid flow rate L = 4.022 Kg/m^{2}s. Aqueous solution of 60 ppm surfactant produced heavy foam at low liquid flow rate of L = 2.550 Kg/m^{2}s g which simultaneously lowered the dynamic liquid hold saturation. Figure 12 presents the experimental points for foaming aqueous solution of 30 ppm surfactant lies lower than trendlines proposed by [20], [21], [3] and [4]. This confirms that, as the surface tension decreases, β_{exp} in both low and high interaction regimes decreases. The trendline proposed by [11], [18] also showed, for foaming solution of low surface tension, the change in β_{exp} is much prominent and noticeable in high interaction regime.

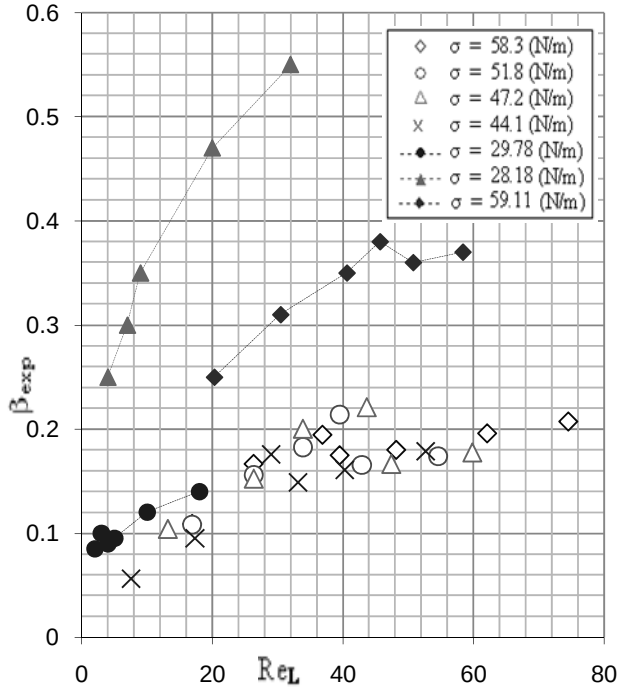

Fig. 12 Comparison of effect of surface tension on β_{exp} for literature data and present investigation. 50% Ethanol – N_2 system at σ = 29.78 N/m [11], [18]; Ethanol – helium at σ = 28.18 N/m [20]; 6ppm surfactant – system at σ = 59.11 N/m [3], [4]. Empty points surfactant – air system at different surface tension for present study G = 0.201 – 0.210 Kg/m^{2}s for all systems.

IV. CONCLUSIONS

It can be concluded that values of dynamic liquid saturation directly depends liquid and gas flow rates. β_{exp} or dynamic liquid saturation increases with increase in liquid flow rate in low interaction regime (GCF) and then decreased sharply with the change in regime transition to high interaction regime (PF/FPF). Whereas this phenomenon observed for non-foaming air-water system was entirely opposite. For 15 ppm aqueous surfactant solution, unchanged β_{exp} values were observed in both low and high interaction regimes. But a significant decrease in β_{exp} was observed in in aqueous solution of 45 and 60 ppm surfactant. Further an increase in gas flow rate leads to decrease in dynamic liquid saturation.

The dependence is not that much similar as observed for non-foaming air-water system. An increase in gas floe rate leads to a much lower values of β_{exp} as compare to air-water system. It is observed that the dynamic liquid saturation is highly dependent on gas superficial velocities in high interaction regime. In high interaction regime, β_{exp} decreases with increase in gas flow velocity which is in accordance with the trends observed different researchers. In high interaction regime, 45 ppm and 60 ppm aqueous surfactant solutions of least surface tension (47.4 N/m and 44.2 N/m respectively) yielded to significantly low values of β_{exp} or dynamic liquid saturation.

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