Liquid Holdup in Concurrent Gas Liquid Upflow Through Packed Column with Random and Corrugated Structured Packing

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Abstract—**Liquid holdup in packed columns is one of the significant parameter for the efficiency of unit operations and process. The column internals play a major role in the performance of packed bed reactor. Structured packings posses high surface area. Little information is available on hydrodynamics. In the present study corrugated structured packing of Finepac 500Y and Finepac 250Y were used and compared with other packings namely ceramic spheres, Raschig rings and Intalox saddles of different sizes. A column of 9.025 cm diameter and 1 m height was used as packed bed unit. Wide range in gas-liquid flow rates and properties of air-water, air-Glycerol and air-MEA were used. The total and dynamic liquid holdups were determined using these systems with above packings. Liquid holdup was found to be more than 50% higher in corrugated structured packings than random packings. Correlations were developed for total and dynamic liquid holdups in corrugated structured packings and as well as random packings. For random packings the total and dynamic liquid holdups were observed to decrease with gas flow rate, increase with liquid flow rate, with viscosity of the liquid and combine effect of bed porosity and size of the packing was observed on both liquid holdups. For corrugated structured packings both holdups have very little effect with liquid flow rates, bed porosity and decreases with gas flow rates.**

Index Terms— gas-liquid up-flow, liquid holdups, packed bed reactor, structured packing

I. INTRODUCTION

PACKED beds are widely used for solid catalyzed heterogeneous reactions and mass transfer operations. Different packings are being tried for the efficiency of the operations. Of late research is going on in packed beds with structured packing posses high surface to volume ratio. An attempt has been made to study the hydrodynamic parameters using these structured packing and also random packings in concurrent gas liquid upflow through packed bed. Among these parameters, liquid holdup is one of the significant design variable.

However reports in literature predict the liquid holdup/saturation with packings other than structured packings. Much of the work is related to the flow of single gas-liquid system i.e. air-water as in [2], [6], [7], [9]-[12], [17], [18], and [20]. Others who studied single gas-liquid systems are, as in [4], [8], [14] and [15]. A few authors investigated the liquid holdup with more than one system, as in [1], [3], [5], [16], and [19]. Similarly most of the authors used only one type of packing, as in [2], [6], [9]-[12], [15], [17]-[18]. Few authors investigated the liquid holdup/saturation with more than one type of packing as in [1], [7], and [16]. Only [16] experimented with more than one type of packing and more than one gas-liquid system. The gas liquid flow rates selected by majority of the investigators are such that they cover bubble and early stages of pulse flow.

The literature survey shows the data on liquid holdup limited with respect 1) to type and sizes of packing 2) to high liquid flow rates and corresponding gas flow rates to cover the three flow regimes, namely bubble flow, pulse flow and spray flow 3) to effect of physical properties of the liquid phase. Reported correlations in literature for the estimation of liquid holdup/saturation, are restricted to a limited range of parameters in terms of packing size, bed porosity and physical properties of the liquid systems. In this study attempt has been made to work a) over a large range of column packing (Raschig rings, two sizes of Intalox saddles and three sizes of spheres & corrugated structured packing of two sizes) b) over a wide range of fluid flow rates covering all the flow regimes ($0.265 \leq G$ (kg/m^2s) ≤ 1.768, $3.53 \leq L$ (kg/m^2s) ≤ 43.92) and c) over a wide range of variation in viscosity of the liquid phase.

There are no published reports on liquid holdup in concurrent gas-liquid up flow through packed column with corrugated structured packing. In the present study correlations have been developed each for the estimation of total and dynamic liquid holdup in terms of physical characteristics of the fluids, packing and the operating parameters for both corrugated structured and random packings.

II. EXPERIMENTAL

The schematic diagram of the experimental packed column is shown in Fig. 1 to measure the liquid holdups. The liquid holdup is defined as the volume of the liquid per unit volume of the column. For non porous particles, the total liquid holdup can be split in to dynamic and static liquid holdup, $\varepsilon_t = \varepsilon_d + \varepsilon_s$. The packed column is constructed with Perspex pipe of internal diameter 0.9025 cm and a height of 100 cm. The gas and liquid are fed to the gas

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liquid distributor provided at the bottom of the column and at the top a gas liquid separator is provided. Air from the compressor passes through the gas rotameter to the gas-liquid distributor. The liquid from the storage tank is pumped by a centrifugal pump through the liquid rotameter to the same gas-liquid distributor. The gas and liquid are brought into contact at the bottom of the packed column and they pass concurrently upwards through the column to the gas liquid separator where liquid separates from gas. The liquid returns to the storage tank. Two solenoid valves are provided, each in the feed lines of gas and liquid before the gas-liquid distributor. Just before these valves a quick connecting /disconnecting joints are provided. With these joints the column can be disconnected from the gas and liquid lines to facilitate to measure its weight. The entire column is erected on an electronic balance. This balance is used to measure the liquid holdup in the column. The flow rate of the gas and liquid are set at desired rates and after steady state is reached gas and liquid flow rates are stopped simultaneously by using solenoid valves. The column is disconnected from supply lines and then the weight is noted. The column is allowed to drain for 30 minutes and noted the weight again. The difference between the weight of the column with liquid and the dry weight gives total liquid holdup, the difference between the weight of the column after draining and dry weight gives the static liquid holdup. Difference between the total and static liquid holdup gives the dynamic liquid holdup. Experimental runs were performed using different gas-liquid systems: Air-water, Air-56% & 67% Glycerol and Air-MEA, column diameter, $d_c = 9.025 \times 10^{-2}$ m, column height, h= 1.0 m, liquid flow rate, L = 2.17 to 43.422 kg/m^{2}s and gas flow rate, G= 0.265 to 2.388 kg/m^{2}s. Table I gives the packing characteristic and physical properties of fluids.

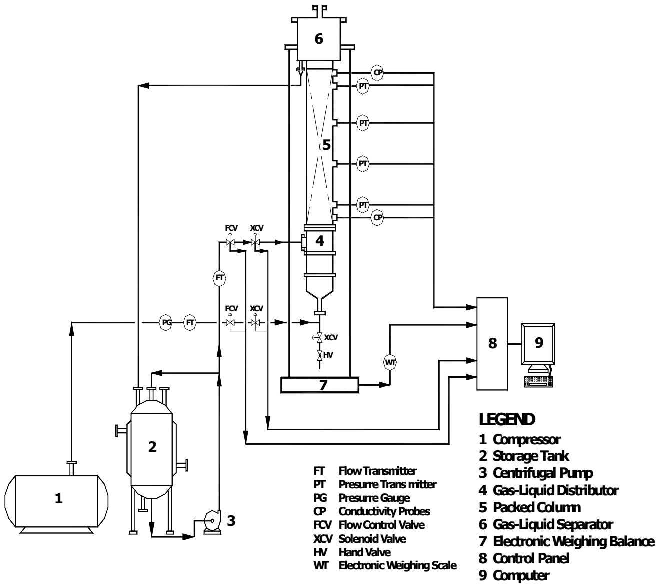

Fig 1: Schematic diagram of the experiment set-up.

Table I: Packing characteristic and physical properties of fluids

(a) Characteristics of corrugated structured packings

Regular packing	E	Dimensions				
		B (mm)	H (mm)	S (mm)	(θ^o)	d_{eq} (mm)
FINEPAC 500Y	0.98	14.4	6.6	10.1	45^0	7.45
FINEPAC 250Y	0.99	29.5	11.3	17.7	45^0	14.57

(b) Characteristics of Random packings

Type	d_p (mm)	ε	Φ
Ceramic spheres	3.87	0.354	1.000
Ceramic spheres	6.90	0.352	1.000
Ceramic spheres	8.52	0.400	1.000
Ceramic Intalox saddles	7.90	0.563	0.514
Ceramic Intalox saddles	8.86	0.066	0.361
Raschig Rings	6.00	0.440	0.580

(c) Physical properties of fluids

Fluid	ρ (kg/m^3)	μ (kg/ms)
Water	1000.00	0.0010
Glycerol (67%)	1167.45	0.0113
Glycerol (56%)	1165.00	0.0070
MEA	1020.00	0.0150
Air	1.17	1.8×10^{-5}

III. RESULTS AND DISCUSSION

(a). Effect of gas rate and liquid flow rates for random and corrugated structured packing

Figs. 2 and 3 indicate the variation of total liquid holdup with variation in gas flow rates for different liquid flow rates for concurrent upflow of air-water through random (spheres 8.54 mm) and corrugated structured packing (Finepac 500Y). These figures indicate that the total liquid holdup decrease with increase in gas flow rate. As the gas velocity increases the mean residence time of the liquid decreases necessarily because of the greater shear at the gas liquid interface, leading thus to a decrease in liquid fraction in the column. The rate of decrease in total liquid holdup is more rapid at low gas flow rates than at high gas flow rates for both the packings. For a particular liquid flow rate, the sudden increase in the gas expands into the space restricting the liquid flow rate. However at a higher gas flow rate, the liquid holdup is almost same. The dynamic liquid holdup also follows similar trend.

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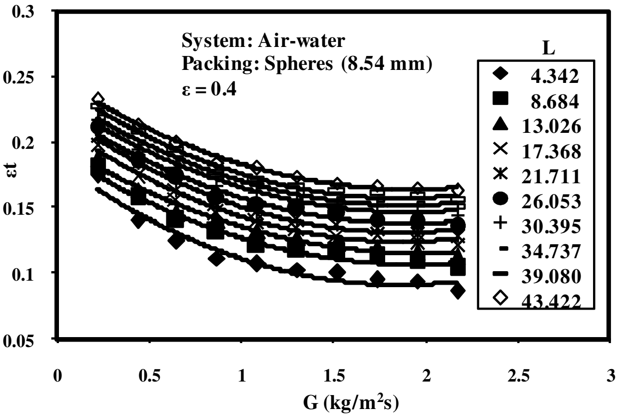

Fig. 2: Variation of total liquid holdup with gas and liquid flow rates for Air-water system through spheres 8.52 mm.

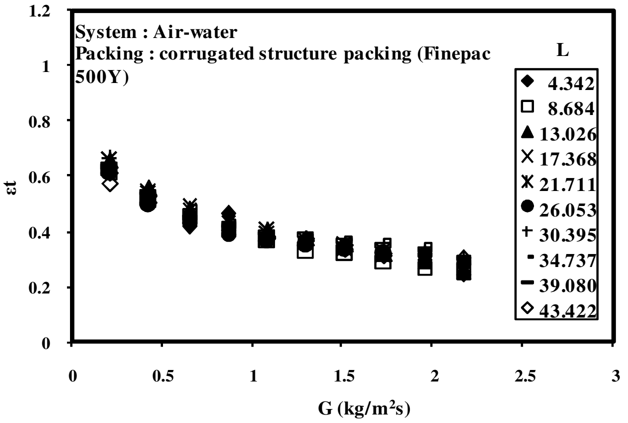

Fig. 3: Variation of total liquid holdup with gas flow rate as a function of liquid flow rate for Air-water system

Fig. 2 also indicates the variation of total liquid holdup with liquid flow rate for concurrent upflow of air-water though spheres (8.52 mm). It can be seen that with increase in the mass flow rate of liquid the total liquid holdup increase. As the liquid flow rate increases, the flowing liquid tends to sweep away the gas bubbles present in the column. The residence time of the gas bubbles in the column decreases, which in turn decreases the gas holdup and hence there is an increase in dynamic liquid holdup. It is however, noted that the liquid holdup is a stronger function of gas flow rate than the liquid flow rate.

Fig. 4 shows the variation of total liquid holdup with liquid flow rates for flow of air-water through corrugated structured packing Finepac 500Y. In this case influence of liquid flow rate is very little on the total liquid holdup. This observation is due to high porosity, high equivalent diameter and the design of the structured packing, the flowing liquid even at high flow rates is unable to sweep away the gas bubbles present in the column. The dynamic liquid holdup is also affected very little by the increase in the liquid flow rate.

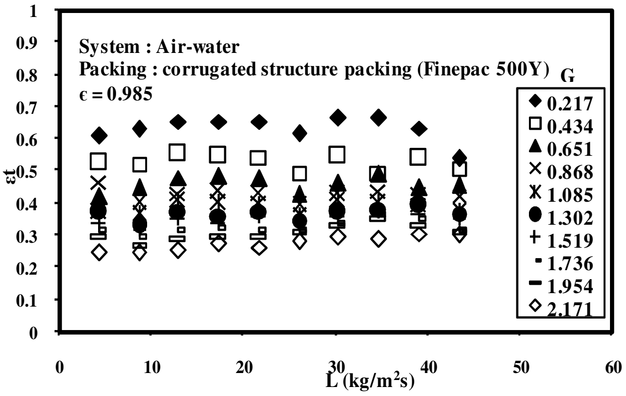

Fig. 4: Variation of total liquid holdup with liquid flow rate as a function of gas flow rate for Air-water system

(b) Comparison of liquid holdup in structured packing with the random packing

Fig. 5 shows the comparison of total liquid holdup in corrugated structured packing with the random packing. For comparison random packing with higher liquid holdup (Intalox saddles 8.86 mm) is compared with structured packing with lower liquid holdup (Finepac 500Y). Liquid holdup in corrugated structured packing is more than 50% compared with random packing because of high porosity. This helps in better heat and mass transfer performances.

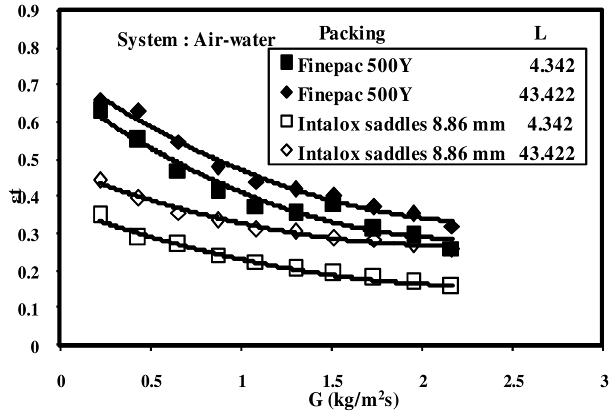

Fig. 5: Comparison of total liquid holdup in corrugated structured packing (Finepac 500Y) with random packing (Intalox saddles 8.86 mm) for air -water system

(c) Effect of physical properties of liquid for random and corrugated structured packing

As mentioned the higher liquid holdups has several advantages, with increase in viscosity this affect is observed with air – MEA system compared to air- 56% Glycerol system as shown in Fig 6 for random packing. Further in corrugated structured packing it is higher for air-67% Glycerol than for air-water system. The fact is that Monoethanolamine has higher viscosity and lower surface tension than 56% Glycerol and the 56% Glycerol has higher viscosity and lower surface tension than water. Increase in liquid viscosity increases the liquid shear stress at the liquid-solid interface as in [5] and hence an increase in total liquid holdup. It is also noted that, increasing the surface tension of the liquid resulted in decreasing the dynamic liquid.

Similarly the dynamic liquid holdup also increases with the increase in viscosity and decrease in surface tension.

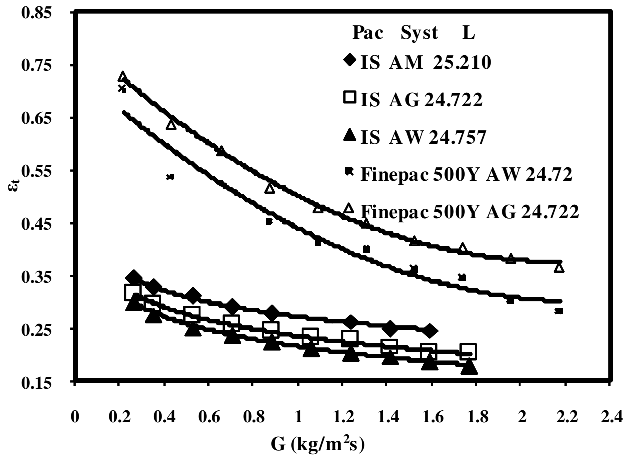

Fig. 6: Variation of ε_t with gas flow rate as a function of liquid flow rate for air-water and air – 67% & 56% Glycerol through Intalox saddles (7.9 mm) and Finepac 500Y.

(d) Effect of packing characteristics for random and corrugated structured packing

Fig. 7 indicates the variation of total liquid holdup with variation in structured packings. It can be seen that total liquid holdup is influenced very little with the different sizes of structured packing. This is observed because the porosity of all the structured packing is almost same, which is of the order of 0.95 a good feature for gas-liquid contact. Figure 8 indicates the variation of total liquid hold up with variation of packing for flow of air-56% Glycerol system. It can be noticed that the total liquid hold up increase with increase in bed porosity and also increases with packing size but intalox saddles of size 7.9 mm gave higher liquid holdup than spheres of size 8.52 mm. Therefore combined effect of bed porosity and size of packing on liquid holdup was observed.

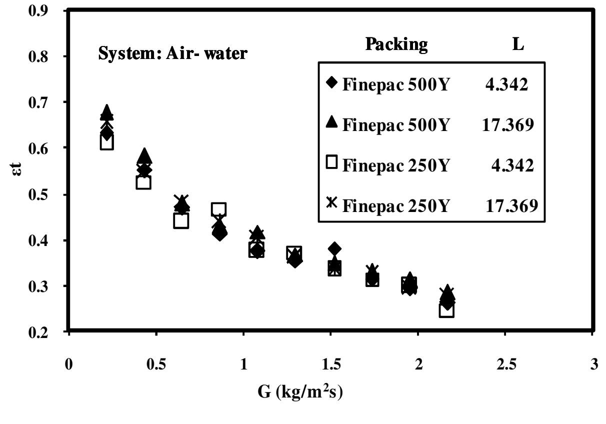

Fig.7: Variation of total liquid holdup with gas flow rate as a function of liquid flow rate for two sizes of structured packing

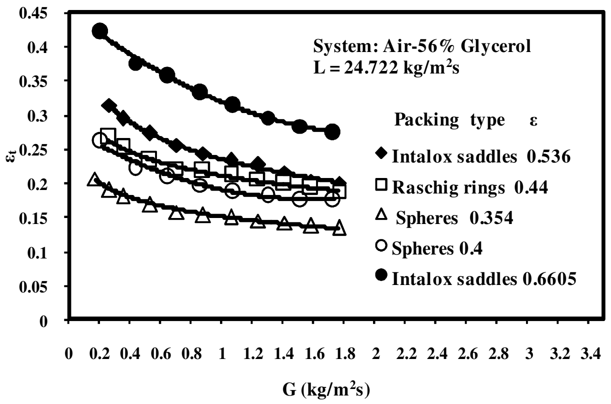

Fig. 8: Variation of ε_t with type of packing for air-56% Glycerol system

IV. CORRELATION OF EXPERIMENTAL DATA

New correlations were developed for total and dynamic liquid holdup in corrugated structured packing holdup in terms of Reynolds number of gas and liquid, packing characteristics and physical properties of system. It is observed that the total and dynamic liquid holdups are dependent on gas flow rate; physical properties of the gas-liquid systems, and the packing characteristics used, but do not depend on liquid flow rate. Using regression analysis the data of total and dynamic is correlated successfully. Using (1)-(2), total and dynamic liquid holdup is calculated.

$$\varepsilon_t = 5.62\ \mathrm{Re}_L^{\,0.049}\ \mathrm{Re}_G^{\,-0.3346}\left(\frac{d_{eq}}{d_c}\right)^{0.358}\left(\frac{\mu_L}{\mu_w}\right)^{0.11} \tag{1}$$

$$\varepsilon_d = 7.1\ \mathrm{Re}_L^{\,0.0524}\ \mathrm{Re}_G^{\,-0.37}\left(\frac{d_{eq}}{d_c}\right)^{0.43}\left(\frac{\mu_L}{\mu_w}\right)^{0.12} \tag{2}$$

Fig. 9 shows the comparison of predicted verses experimental total liquid holdup. The deviation was found to be 5.25% from the experimental values. Similarly for the dynamic liquid holdup the deviation was found to 5.5% from the experimental values.

For random packing correlation in terms of physical characteristics of the fluids, packing and the operating parameters has been developed. Using regression analysis the data is correlated successfully. Total liquid holdup is predicted by using (3).

$$\varepsilon_t = 1.489\,\mathrm{Re}_L^{\,0.142}\ \mathrm{Re}_G^{\,-0.222}\left(\frac{\varepsilon}{1-\varepsilon}\right)^{0.547}\left(\frac{d_p}{d_c}\right)^{0.054}\left(\frac{g\mu_L^{\,4}}{\rho_L\sigma_L^{\,3}}\right)^{0.054} \tag{3}$$

The predicted values with the experimental values agree very well. The deviation was found to be 6.0% from the experimental values. In earlier correlations the effects of liquid properties have not been included which have influence on the liquid holdup depicted as in (3). Morton number ($g\mu^4/\rho\sigma^3$) is the function of fluid phase properties which relates viscous and surface forces.

Similarly dynamic liquid holdup is correlated successfully. Using (4), dynamic liquid holdup was calculated and the deviation was found to be 7.5% from the experimental values.

$$\varepsilon_d = 1.90 \mathrm{Re}_L^{\,0.1952} \mathrm{Re}_G^{\,-0.302} \left(\frac{\varepsilon}{1-\varepsilon}\right)^{0.639} \left(\frac{d_p}{d_c}\right)^{-0.007} \left(\frac{g\mu_L^{\,4}}{\rho_L \sigma_L^{\,3}}\right)^{0.076} \quad (4)$$

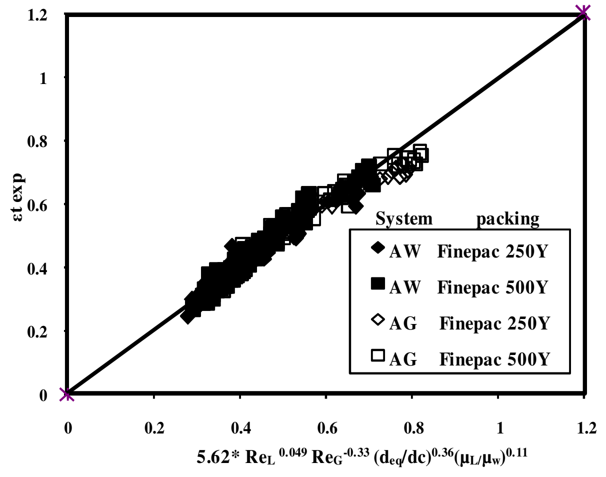

Fig. 9: Comparison of present experimental total liquid holdup data with the prediction using (1).

V. CONCLUSIONS

New correlations were developed for total and dynamic liquid hold up in corrugated structured and random packings. Liquid holdup is high in corrugated structured packing when compared with random packing. For random packings it is observed that the total and dynamic liquid holdups decreases with gas flow rate, increases with liquid flow rate, and with viscosity of the liquid and combine effect of bed porosity and size of the packing was observed on both liquid holdups. For corrugated structured packings both holdups have very little effect with liquid flow rates and bed porosity and decreases with gas flow rates. The total and dynamic liquid holdup correlations for structured packings predict the present data with root mean square deviation of 5.25% and 5.5% respectively and correlations for random packing predict the present as well as literature data with RMS deviation of 6.0% and 7.5% respectively.

NOMENCLATURE

a_v	Surface area of the corrugated structured packing, m^2/m^3, (Bravio 1985)
B	Corrugation base length, m
d_p	Particle diameter, m
d_{eq}	Equivalent diameter of corrugated structured packing
G	Gas flow rate, kg/m^2 s
H	Corrugation height, m
h	Packed column height, m
L	Liquid flow rate, kg/m^2 s
n	Number of observations
Re	Reynolds number, ($dp\ G / \mu_G$) or ($d_{eq}\ G / \mu_G$)
S	Corrugation side length, m

Greek symbols

ε_t	Total liquid holdup
ε_d	Dynamic liquid holdup
ε_s	Static liquid holdup
ε	Bed porosity
μ	Viscosity, kg/ms
σ	Surface tension N/m
ρ	Density kg/m^3
θ^o	Corrugation angle of the corrugated structured packing
ϕ	Sphericity

Abbreviations

exp	experimental
pre	predicted
L	liquid
G	gas
AW	air-water
AG	air-Glycerol
MEA	Monoethanolamine
RMS	Root mean square deviation

$$\sqrt{\frac{1}{n}\sum_{1}^{n}\left(\left(x_{exp} - x_{pre}\right)\Big/ x_{exp}\right)^2}$$

IS	Intalox saddles

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