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Liquid holdup in turbulent bed contactor

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Abstract

Experimental data on liquid holdup are collected over a wide range of variables in a turbulent bed contactor (TBC) with a 3 mm projection of the gasket to block the free area of the distributor plate near the wall so that the channeling of liquid along the wall is avoided. The variation in dynamic liquid holdup based on static bed height $\varepsilon_{\mathrm{ld,st}}$ with gas velocity, liquid velocity, particle diameter and density, static bed height, free-open area of the distributor plate and dimensions of downcomer are discussed for Type I and Type II turbulent bed contactor. Correlations are developed to predict the dynamic liquid holdup. The liquid holdup obtained through quick closing valve technique is compared with the liquid holdup obtained through residence time distribution (RTD) method.

Keywords: Fluidization; Three phase fluidization; Turbulent bed contactor; Liquid holdup; Downcomer

1. Introduction

The turbulent bed contactor (TBC) is a countercurrent gas–liquid–solid fluidization system with the gas serving as the continuous phase and liquid as dispersed phase in which relatively low density inert particles are used to enhance the contact between the flowing fluid phases. Two types of operations (Type I and Type II) are possible in a TBC depending on the density of the particles [1]. In Type I TBC operation, with low density particles ($\rho_p \leq 300\,\mathrm{kg/m^3}$), the onset of fluidization occurs at a gas velocity lower than the flooding velocity for the equivalent countercurrent packed bed. In Type II TBC operation, with a density of particles greater than $300\,\mathrm{kg/m^3}$, the onset of fluidization of the particles occurs at the flooding point. The flow regimes in TBC have been recently described by Bruce et al. [2]. TBC has been used for physical, chemical and biological processing. In physical processing, the TBC is used in air-cooling, humidification and dehumidification, particulate removal and lactose granulation. In chemical processing, they are employed in flue gas desulphurization, absorption, desorption and distillation. In biological processing it is used for alcohol fermentation. Some specific applications are discussed by Fan [3].

For any multiphase contacting equipment, one of the fundamental operating characteristics is its liquid holdup. Other characteristics namely pressure drop, interstitial velocity, interfacial area and bed expansion in turn depends on liquid holdup. Empirical correlations proposed by various investigators to predict liquid holdup in TBCs are summarized by Fan [3], Ercan et al. [4] and Soundarajan [5] for Type I and Type II operations.

The liquid holdup in a TBC consists of the operational or dynamic holdup and static holdup. The dynamic liquid holdup can be measured by collecting the liquid either in the bed or at the bottom of the bed after simultaneously shutting of gas and liquid flows. The other methods of measuring liquid holdup are tracer technique and pressure drop. According to Vunjak-Novakovic et al. [6], the pressure drop method is widely used even though this method is not very accurate because of the uncertainty involved in measuring the expanded bed height and the fluctuations in the pressure drop. Rama et al. [7] and Paterson and Clift [8] mentioned that the concept of equating the pressure drop across the bed to the weight per unit area of the particles plus liquid does not hold good, since all the liquid in the bed is not completely supported by the upward flow of gas as in the conventional fluidized bed. Hence, the liquid holdup measurement by pressure drop method under predicts the actual holdup in the column.

Ercan et al. [4], however, recommended that the pressure drop method using pressure transducers is accurate and easy rather than U-tube manometer. If the entire liquid in the bed is not supported by the upward flow of gas, this method cannot be relied upon. It appears that the method of collecting liquid after simultaneously shutting off gas and liquid flows may be more accurate if proper instrumentation is used.

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Nomenclature

Ar	Archimedes number, $d_p^3\rho_g(\rho_p-\rho_g)g/\mu_g^2$
d_{DC}	inner diameter of downcomer (m)
d_p	diameter of particle (m)
d_0	equivalent diameter of free-opening of supporting grid (m)
D_c	diameter of column (m)
D_e	equivalent diameter for free-open area of supporting grid $D_c(f)^{0.5}$ (m)
$E(t)$	exit age distribution function (s^{-1})
f	free-open area of the supporting grid
f_c	equivalent free-open area of supporting grid, fd_0/D_e
Fr_l	Froude number for liquid phase, $u_l/(gd_p)^{0.5}$
g	acceleration due to gravity, 9.807 m/s^2
h_w	weir height of downcomer (m)
H	height of the expanded bed (m)
H_0	static bed height (m)
J	objective function
Pe	Peclet number
Q_l	liquid flow rate (m^3/s)
Re_l	Reynolds number for liquid phase, $d_p u_l \rho_l/\mu_l$
S	cross-sectional area of empty column (m^2)
$\bar{t}$	average residence time (s)
u_g	superficial gas velocity (m/s)
u_l	superficial liquid velocity (m/s)
u_{mf}	minimum fluidization velocity (m/s)
V_l	volume of liquid held in the bed (m^3)
V_{ld}	volume of dynamic liquid held in the bed (m^3)
V_p	volume of solid in the bed (m^3)

Greek Letters

ε_g	gas holdup, V_g/SH (m^3/m^3)
ε_l	liquid holdup, V_l/SH (m^3/m^3)
ε_{ld}	dynamic liquid holdup, V_{ld}/SH (m^3/m^3)
$\varepsilon_{ld,st}$	dynamic liquid holdup based on static bed volume (m^3/m^3)
ε_p	solid holdup V_p/SH (m^3/m^3)
ε_0	voidage of the static bed without gas–liquid flow (m^3/m^3)
μ_g	viscosity of the gas (Pa s)
μ_l	viscosity of the liquid (Pa s)
ρ_g	density of the gas (kg/m^3)
ρ_l	density of the liquid (kg/m^3)
ρ_p	density of the particle (kg/m^3)

Subscripts

g	gas
l	liquid
p	particle
w	weir

Table 1
Range of variables

Variable	Range
Gas velocity, u_g (ms^{-1})	1–5
Liquid velocity, u_l (ms^{-1})	0.0014–0.0096
Static bed height, H_0 (m)	0.07, 0.107, 0.113, 0.147, 0.17, 0.226
Distributor plate free-open area, f	0.70, 0.82
Particle diameter, d_p (m)	0.012, 0.0125, 0.016, 0.025
Particle density, ρ_p (kg m^{-3})	110, 145, 215, 608, 835
Downcomer diameter, d_{DC} (m)	0.018, 0.025
Downcomer weir height, h_w (m)	0.03, 0.06, 0.09

Soundarajan [5] analyzed the correlations reported in the literature and concluded that the liquid holdup depends on liquid velocity, free-open area of the distributor plate, static bed height and diameter of the particle, and independent of gas velocity in Type I TBC operation; specifically, liquid holdup increases with increase in liquid velocity (to a power of 0.6–1.05), decrease in particle size (−1.289 to −0.5), static bed height (−1 to −0.36) and free-open area (−0.58 to −0.4). In case of Type II TBC, liquid holdup increases with increase in liquid velocity (0.3–1) and density of the particle (0.09–0.18), decrease in diameter of the particle (−0.84 to −0.07), static bed height (−0.6 to −0.4) and free-open area (−0.84 to −0.58). Recently Gimenes and Handley [9] reported hydrodynamics during their study of particle collection in TBC using perforated spheres, oblate spheroid and spherical particles. In their study, it was noted that the liquid holdup increases with increasing liquid flow rate and decrease with static bed height. It remains almost constant with increase in gas velocity except near to 'true' flooding. The range variables studied is given in Table 1.

Based on the range of applicability, Fan [3] suggested that for Type I TBC, the correlations proposed by Gel'perin et al. [10], Kito et al. [11], Rama et al. [7] and Vunjak-Novakovic et al. [6] can be used for predicting the liquid holdup. For Type II TBC, the correlations given by Kito et al. [11] and Vunjak-Novakovic et al. [6] are recommended. However, Ercan et al. [4] recommended the correlations developed by Chen and Douglas [12] and Uysal [13] (cited in [3]) since these correlations are developed for large free-open area without wall effects.

Ercan et al. [4] criticized the use of low free-open area of the distributor plate (<70%), low ratio of the column to particle diameter and noted that the discrepancy in liquid holdup is mainly due to the use of parameters such as free-open area, column to particle diameter ratio. Their objection to the use of low free area of the supporting grid is valid since the definition of TBC based on the gas continuous phase may not be prevalent due to the accumulation of liquid on the supporting grid with small free-open areas. With large free-open areas, it was noticed that most of the liquid was flowing down the wall without contacting the solid particles in the bed [5]. Hence to minimize the channeling of liquid and increase the contact between the three phases, a 3 mm projection in the distributor near the wall was provided in the present study. Because of this projection almost all the liquid circulated within the bed giving rise to more contact between gas and liquid phases.

In the present work it is proposed to conduct experiments to obtain liquid holdup using different types of TBC

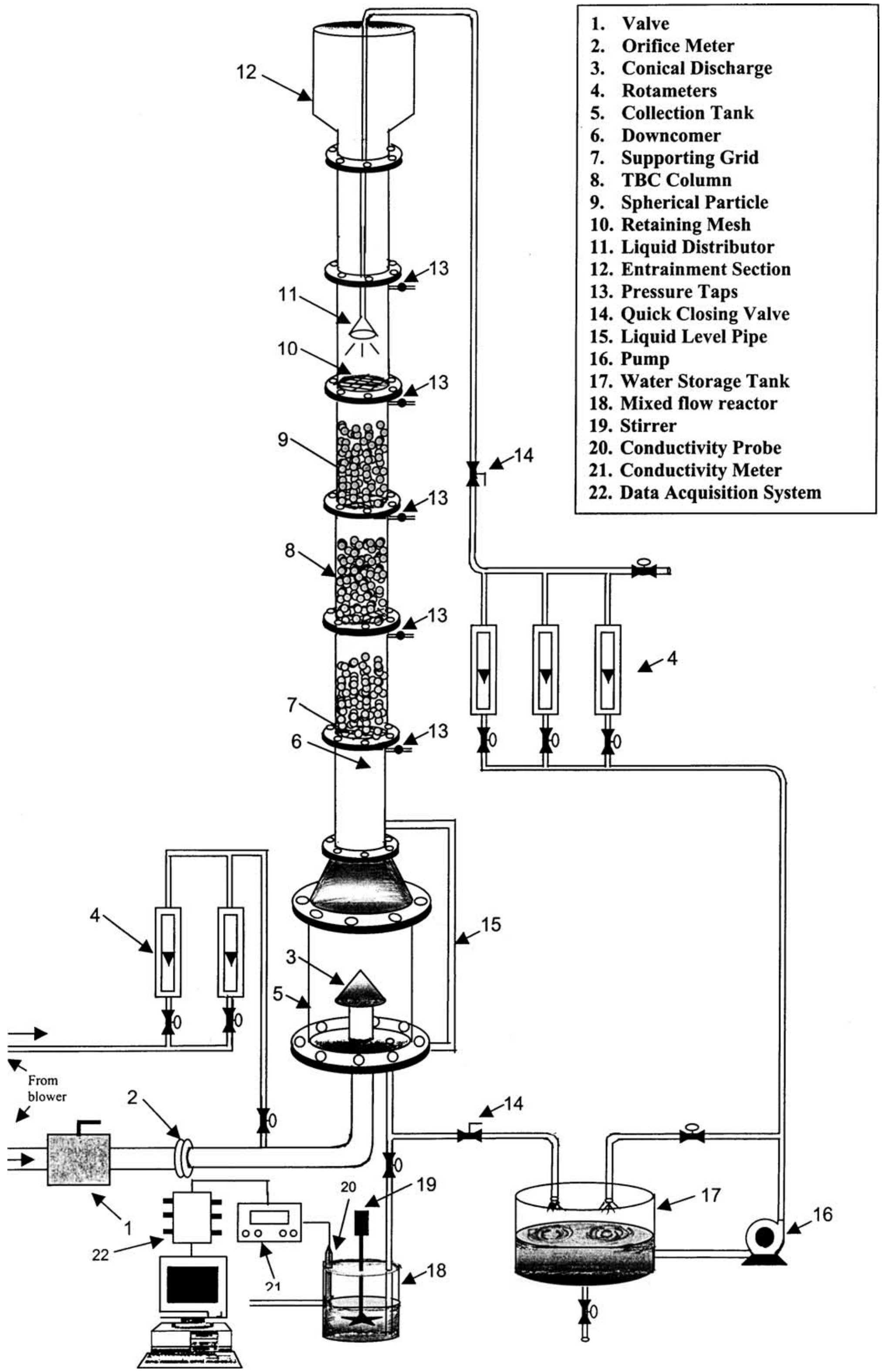

Fig. 1. Schematic diagram of TBC.

operations such as with and without projection from the wall on the distributor, with and without downcomer (DC) for Type I and Type II operations. The experimental liquid holdup at various parameters such as gas and liquid flow rates, free-open areas of the supporting grid, diameter and density of the particles, static bed height and, diameter and weir height of downcomer are collected. Correlations are proposed to predict the liquid holdup for different operations.

2. Experimental

The schematic diagram of experimental setup is shown in Fig. 1. The test section consists of a Perspex column of 113 mm inside diameter with a total height of 3 m, out of which the test section is 1.8 m. The test section can be used either as single stage or multistage. The gas (air) was entered from the bottom of the column to fluidize the particles and the liquid was sprayed countercurrently from the top. The gas flow rate was measured by using rotameters and/or orifice meter, while the liquid flow rate was measured by rotameters. A specially designed downcomer [2,14] was used for the experiments on TBC with DC. A schematic diagram of the downcomer used in the present work is shown in Fig. 2. It has a conical bottom, which has been designed to be self-sealing to prevent the gas from flowing up through the downcomer. The conical shape of the downcomer minimizes the disturbance in the fluidizing bed in multistage operation. This type of downcomer is different from the conventional segmental type, normally used in distillation columns. A rigid wire was tied across the mouth of the downcomer (Fig. 2) in order to prevent the particles from falling into it.

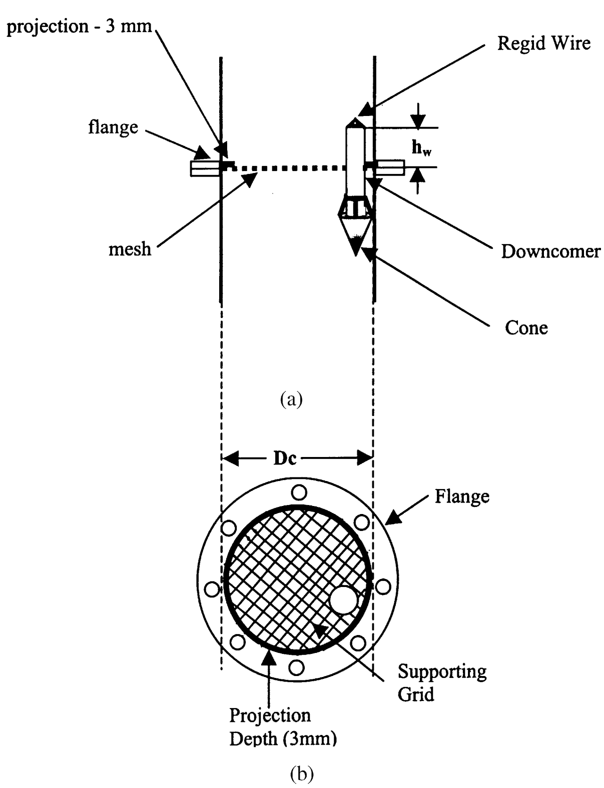

Fig. 2. Details of projection (a) used in the present study and (b) downcomer.

RTD experiments were conducted with and without downcomer. During RTD experiments with downcomer, the conductivity probe was placed inside the downcomer to obtain the exit tracer concentration. This technique should satisfactorily represent the tracer concentration at the exit of the bed. During RTD experiments without downcomer, on the other hand, a novel technique was used to obtain the exit tracer concentration. This was because of the difficulties in obtaining a representative tracer concentration across the entire cross section of the bed and the residence time of the liquid phase was very less (in the order of seconds). In this technique, the residence time of the liquid phase was increased by connecting an ideal MFT of 2.4 l capacity in series with the TBC. The exit concentration of the tracer was measured by means of an on-line conductivity measurement in which a conductivity probe was inserted near the outlet of the MFT. The exit tracer concentration measured by the conductivity probe in either of the methods was acquired by online data acquisition system (see Fig. 1).

In a typical experiment, a particular free-open area of the supporting grid, static bed height, and particle size and density were chosen, and a known liquid flow rate was allowed into the column countercurrent to a particular gas rate. At steady state, which was indicated by constant liquid level in the collection tank and constant pressure drop in the manometer, the liquid level in the collection tank was noted. By using quick closing valves, the liquid and gas flow were cut off simultaneously. The increase in the liquid level was noted by allowing sufficient time to drain the liquid from the bed. Using these values, the holdups of the phases could be calculated. For collecting data on liquid holdup in the presence of downcomer, the same procedure mentioned above was repeated after choosing a particular diameter and weir height of the downcomer. The range variables studied is given in Table 1.

In a typical RTD experiment, a particular set of parameters mentioned above were chosen and the online tracer measurement setup was switched on. A known liquid flow rate was allowed into the column countercurrent to a particular gas flow rate and waited for steady state. After confirming the steady state, a pulse input of a tracer (5 ml of 5N NaCl solution) was injected just above the liquid distributor by means of a medical syringe. Care was taken to inject the tracer within the shortest time period possible (1/10th of a second). The tracer concentration was recorded by a data acquisition system in terms of voltage, which was calibrated in terms of concentration of tracer.

3. Results and discussion

3.1. Comparison of liquid holdup in TBC with and without projection

During the earlier experimental studies [5], it was observed that some of the liquid sprayed at the top of the column was sliding down over the wall and through the distributor without contacting the solid and gas phases. Hence, it was thought that the channeling of liquid could be eliminated to some extent and thereby the contact between the phases can be improved by blocking the holes of the distributor near the wall with a projection of the gasket into the column. To validate the above assumption of projection reducing the channeling of liquid and improving the contact of the phases, experimental data are collected using particles of density 215 kg/m^3 without projection and with 3 mm projection.

The dynamic liquid phase holdup is calculated using the following equations:

$$\varepsilon_{\mathrm{ld}} = \frac{V_{\mathrm{ld}}}{SH} \tag{1}$$

$$\varepsilon_{\mathrm{ld,st}} = \frac{\varepsilon_{\mathrm{ld}} H}{H_0} \tag{2}$$

Eq. (2) is based on static bed height. The experimental gas holdup is estimated from the equation

$$\varepsilon_{\mathrm{g}} = 1 - (\varepsilon_{\mathrm{l}} + \varepsilon_{\mathrm{p}}) \tag{3}$$

where

$$\varepsilon_{\mathrm{l}} = \frac{V_{\mathrm{l}}}{SH} \tag{4}$$

and

$$\varepsilon_{\mathrm{p}} = \frac{V_{\mathrm{p}}}{SH} = (1 - \varepsilon_0)\frac{H_0}{H} \tag{5}$$

The comparison of liquid holdup in terms of volume of liquid with and without projection for a given set of conditions is shown in Fig. 3. From the figure, it is evident that the liquid holdup in the column is more with projection compared to without projection indicating that there is a channeling of liquid along the wall and through the distributor when projection was not used. By providing the projection, the liquid sliding near the wall is obstructed and the liquid tries to flow down the stage over the projection. Under these conditions, the liquid experiences the drag exerted by the gas on the liquid and the liquid is thrown into the bed, thus increasing the contact between the phases. Under the present experimental conditions, the minimum and the maximum increase in liquid holdup in the presence of projection is 20 and 40% in fluidization regime, respectively.

3.2. Liquid holdup in Type I TBC

3.2.1. Without downcomer

The experimental data on liquid holdup are collected over a wide range of variables with a 3 mm projection of the gasket to block the free area of the distributor plate near the wall. The variation in dynamic liquid holdup based on static bed height, $\varepsilon_{\mathrm{ld,st}}$, with gas velocity, liquid velocity, particle diameter and density, static bed height and free-open area of the distributor plate is shown in Figs. 4–10. It can be seen from the figures that the liquid holdup is almost independent of gas velocity, increases with increase in liquid velocity, decreases with increase in particle diameter, static bed height and free-open area of the distributor plate. Similar observations are made by Chen and Douglas [12], Rama et al. [7], and Gimenes and Handley [9]. Gimenes and Handley [9] observed that the liquid holdup increases with increase in static bed height but their correlation shows a negative exponent.

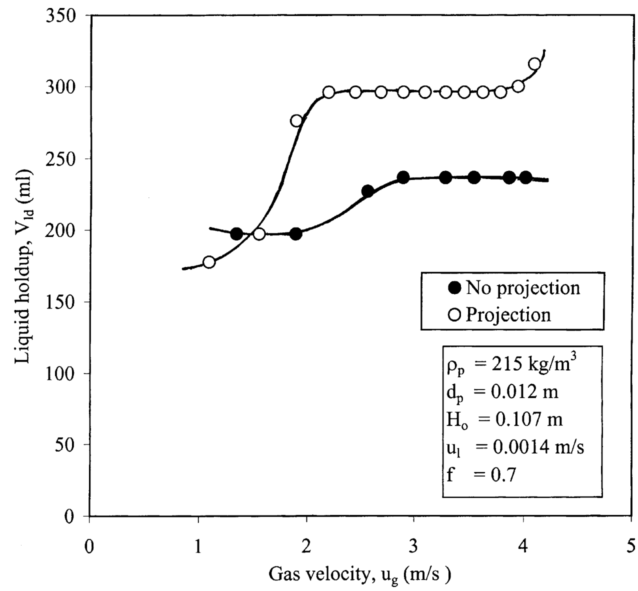

Fig. 3. Comparison of liquid holdup with and without projection.

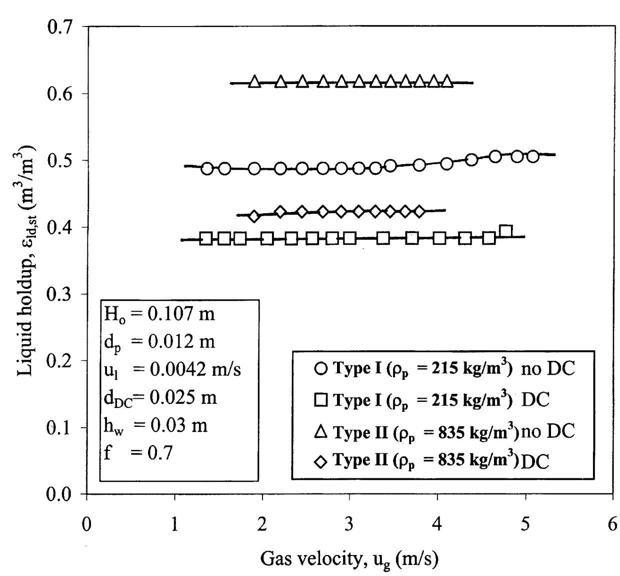

Fig. 4. Effect of gas velocity on liquid holdup.

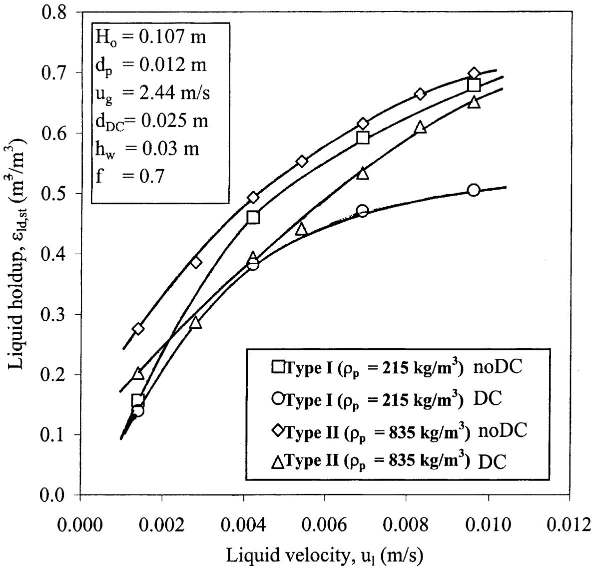

Fig. 5. Effect of liquid velocity on liquid holdup.

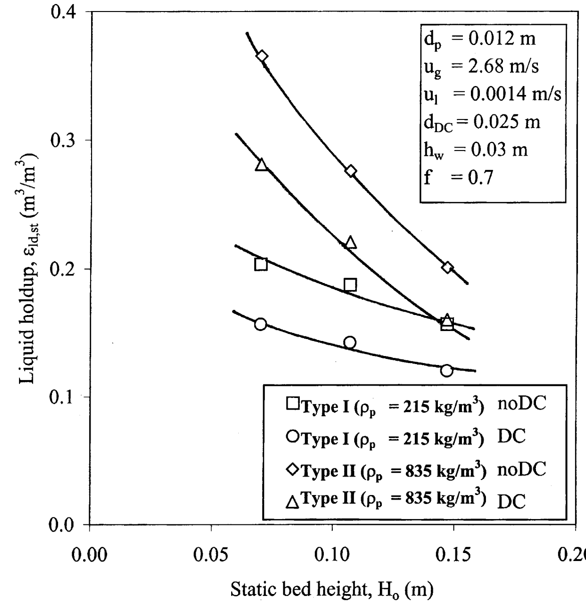

Fig. 7. Effect of static bed height on liquid holdup.

Chen and Douglas [12] lucidly explained the reasons for almost constant liquid holdup with increase in gas velocity based on packed bed behavior. Accordingly, it is reported that the total liquid holdup in packed bed is generally considered to consist of static liquid holdup and dynamic liquid holdup. The dynamic liquid holdup contributes effectively to interfacial transport processes but the static liquid holdup is limited in its contribution.

Extensive data on packed bed have shown that both dynamic and static holdups are independent of gas velocity until the loading point is reached [15–17]. Beyond the loading point liquid holdup raises rapidly. In TBC, flooding velocities are extremely high. Most of the experimental data of the present work, and the data of Chen and Douglas [12] and Rama et al. [7] are collected below flooding conditions. These results show that there is no sudden change of liquid holdup with gas velocity suggesting that the operation is stable and below flooding. Hence, it may be concluded that the gas velocity ranging from 0.5 to 4 m/s, shown in Fig. 4, is below the loading velocity (flooding) of the contactor and therefore from the knowledge on fixed bed the effect of gas velocity on liquid holdup should not be expected.

From Fig. 5, it can be seen that an increase in liquid velocity increases liquid holdup in the bed. This may be due to the increase in interstitial gas velocity in the presence of more liquid flow which occupies more cross-sectional area. The increase in interstitial velocity may exert a drag on the

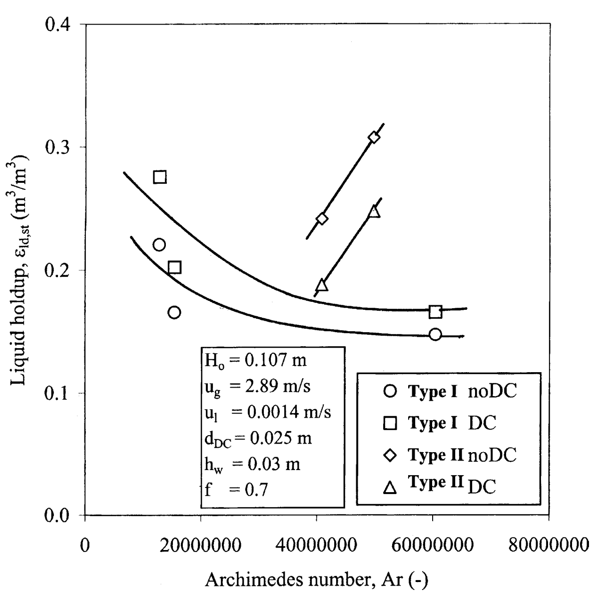

Fig. 6. Effect of particle diameter on liquid holdup.

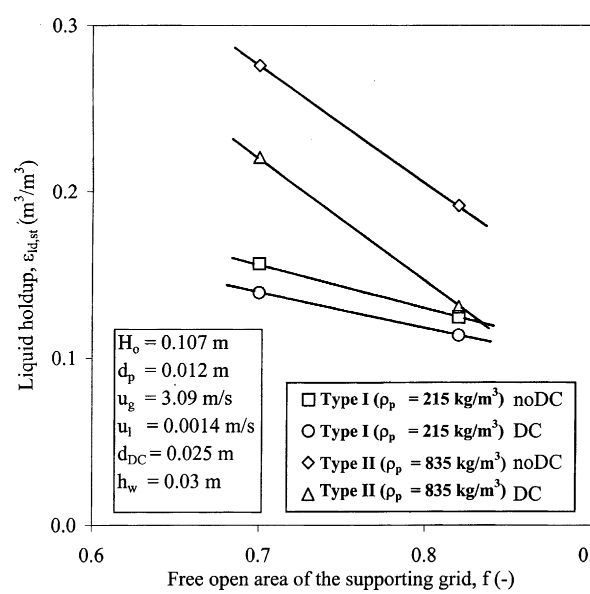

Fig. 8. Effect of free-open area of the supporting grid on liquid holdup.

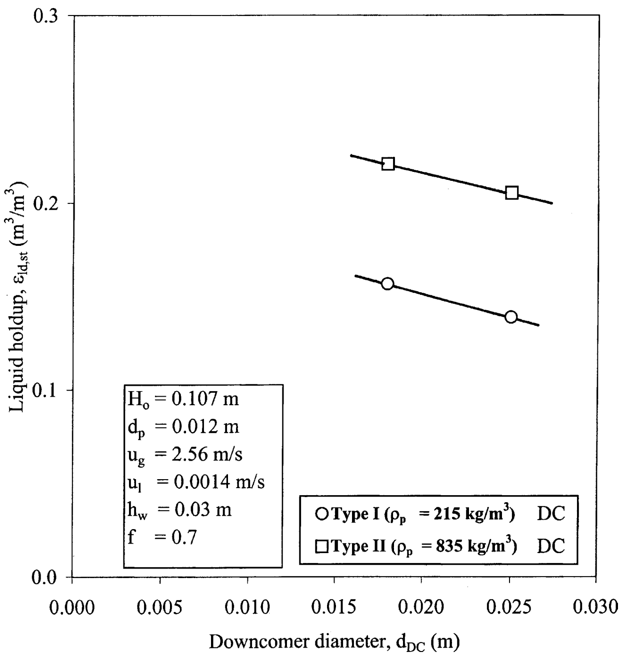

Fig. 9. Effect of downcomer diameter on liquid holdup.

liquid flowing down the bed, impeding the liquid flow, which increases the amount of liquid retained in the bed.

The liquid holdup decreases with increase in Archimedes number (Fig. 6). In Type I TBC, it is found that the density of the particle does not affect the characteristic of the bed [6]. Hence, it can be considered that the liquid holdup decreases with increase in particle diameter as in Fig. 6. As the particle size increases, the surface area per unit volume of bed decreases and hence, less liquid flows on the surface of the particles. As shown in Fig. 7, the liquid holdup decreases with increase in static bed height. Increase in static bed height increases number of particles in a given volume and to accommodate the extra volume of the particles the system adjusts with less amount of liquid in the bed. The increase in free-open area of the distributor plate can accommodate less amount of liquid in the bed (Fig. 8), since the velocity of the gas at the perforation is less and cannot hold more liquid in the system. Based on the experimental data, the following correlation is proposed for liquid holdup in terms of operating variables:

$$\varepsilon_{\mathrm{ld,st}} = 2.01 Re_{\mathrm{l}}^{-0.655}\, Fr_{\mathrm{l}}^{1.06} \left(\frac{H_0}{d_{\mathrm{p}}}\right)^{-0.853} f_{\mathrm{c}}^{-0.203} \tag{6}$$

The correlation predicts the data with a RMS deviation of 9.6%.

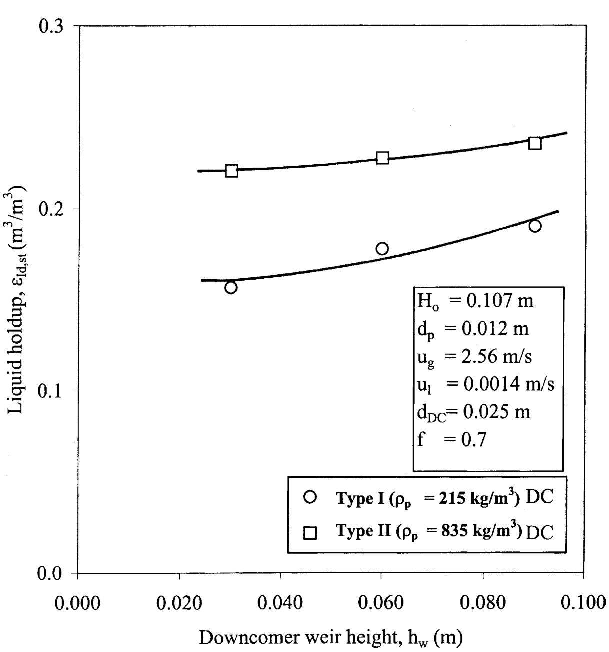

Fig. 10. Effect of downcomer weir height on liquid holdup.

3.2.2. With downcomer

In the present work, a downcomer is used to enhance the range of operation of gas velocities. Soundarajan and Krishnaiah [18,19] are the first to use the downcomer to enhance the gas treating capacity. However, a low free area ≤70% was used in their experiments. In the present work, the downcomer is used in the presence of large free area and at higher gas velocities.

The effect of gas and liquid velocities on dynamic liquid holdup is shown in Figs. 4 and 5. The gas velocity does not show any effect on liquid holdup, whereas liquid holdup increases with increase in liquid velocity. The increase in liquid holdup with increase in liquid velocity is due to more liquid flow in the bed, which increases the interstitial velocity of the gas. This in turn exerts a drag on the liquid film flowing on the particle retaining more liquid in the bed.

It is observed that the liquid holdup decreases with increase in Archimedes number, static bed height, free-open area of the grid, downcomer diameter and downcomer weir height as shown in Figs. 5–10. Even with the downcomer same observations are made without the presence of downcomer in the bed. With increase in downcomer diameter more liquid is discharged (Fig. 9) through the downcomer when compared to the countercurrent flow of gas and liquid through the same perforations of the grid. Fig. 10 presents the variation of liquid holdup with downcomer weir height. It can be seen that the increase in weir height increases the liquid holdup, since sufficient liquid has to be build up for overflowing through the downcomer to the stage below.

Based on the experimental data a correlation has been developed to predict the liquid holdup in terms of the variables mentioned above as

$$\varepsilon_{\mathrm{ld,st}} = 0.033 u_{\mathrm{l}}^{0.576} d_{\mathrm{p}}^{-0.775} H_0^{-0.894} d_{\mathrm{DC}}^{-0.076} h_{\mathrm{w}}^{0.19} \tag{7}$$

The correlation predicts the experimental liquid holdup with a RMS error of 18%.

3.3. Liquid holdup in Type II TBC

3.3.1. Without downcomer

The liquid holdup data as a function of gas velocity is shown in Fig. 4. The effect of liquid velocity is shown in Fig. 5. It can be seen from Fig. 4 that the liquid holdup is almost constant with gas velocity during complete fluidization regime. The increase in liquid velocity increases the liquid holdup, since at a higher liquid rate more liquid has to flow through the column. Fig. 6 shows the effect of Archimedes number on liquid holdup. With increase in Archimedes number, the liquid holdup increases as observed by Vunjak-Novakovic et al. [6] and Ercan et al. [4]. These authors noted that the liquid holdup increases with increase in density of the particles for Type II operation. In the present work, the diameter of particle is almost same ($d_p = 12$ and 12.5 mm), whereas the densities are 835 and 608 kg/m^3 correspondingly. Hence, it may be considered that the change in Archimedes number is mainly due to the density of the particle.

An increase in static bed height decreases liquid holdup as can be seen from Fig. 7. The same trend is also observed by Vunjak-Novakovic et al. [6]. The effect of free area on liquid holdup is shown in Fig. 8. The liquid holdup decreases with increase in free area, since more liquid cannot be heldup in the bed with large free-open area of the distributor. All the experimental holdup data collected are compared with the predicted using the following proposed correlation:

$$\varepsilon_{\mathrm{ld,st}} = 1.36 Re_{\mathrm{l}}^{-0.927}\, Fr_{\mathrm{l}}^{1.44} \left(\frac{H_0}{d_{\mathrm{p}}}\right)^{-0.593} f_{\mathrm{c}}^{-0.213} \qquad (8)$$

The proposed correlation predicts the experimental data within a RMS deviation of 16.2%.

3.3.2. With downcomer

Fig. 4 shows the effect of gas velocity on liquid holdup. As observed earlier in the case of Type II TBC without downcomer, in the present case also liquid holdup is affected by increase in liquid velocity. However, the variation in liquid holdup is significant if comparison is made between the systems with and without DC for Type I and Type II operations as can be seen from Fig. 5. But between the same type of operations the variation is not that significant with or without DC. The same trend is also observed for Type II operation without downcomer. With heavier particles higher gas velocity has to be used to fluidize the particles. These higher gas velocities exert more drag on the fluid flowing on the surface of the particles, which retain more liquid in the bed with higher liquid flow rates.

The effect of Archimedes number is to increase the liquid holdup in the bed as seen from Fig. 6 [4,6]. The change in liquid holdup with increase in static bed is shown in Fig. 7. It is observed that the increase in static bed height decreases the liquid holdup. This may be due to the conversion of actual amount of liquid (V_{l} (cm^3) experimentally collected) to $\varepsilon_{\mathrm{ld,st}}$ based on static bed height. When the increase in liquid holdup (in cm^3) with increase in static bed height is not quite significant and is divided by higher values of static bed height, the decrease in $\varepsilon_{\mathrm{ld,st}}$ is seen with increase in static bed height.

The liquid holdup marginally decreases with increase in free-open area of the grid as shown in Fig. 8. As explained earlier, this is due to more liquid flows down the distributor plate with higher free area, which retains less liquid in the bed. The effect of downcomer diameter and weir height is shown in Figs. 9 and 10, respectively. An increase in downcomer diameter decreases the liquid holdup, since more liquid is transported through the downcomer while an increase in weir height retains more liquid in the bed, since the resistance for flow of liquid is more for more weir height.

The experimental data collected on liquid holdup is compared with the following correlation proposed in the present study:

$$\varepsilon_{\mathrm{ld,st}} = 1.225 u_{\mathrm{l}}^{0.578} \rho_{\mathrm{p}}^{0.145} H_0^{-0.515} d_{\mathrm{DC}}^{-0.247} h_{\mathrm{w}}^{0.062} f_{\mathrm{c}}^{-0.284} \qquad (9)$$

Eq. (9) predicts the experimental data within a RMS deviation of 13.3%.

3.4. Liquid holdup through RTD studies

In the present study, liquid holdup is also characterized through residence time distribution (RTD) studies. Not much work has been reported in the literature on liquid holdup estimation through RTD studies. This may be due to considerable experimental difficulties in obtaining the residence time distribution data for short residence times and the location of the conductivity probe to measure the exit concentration. Chen and Douglas [12] and Rama et al. [20] placed the conductivity cell either at the center or one side of the column which may not represent the tracer concentration inside the bed.

Hence, in the present work it is proposed to evaluate the liquid holdup through RTD studies by increasing the average residence time of the liquid by incorporating an ideal mixed flow tank (MFT) in series with the TBC. Since the RTD of the ideal MFT is known, it can be deconvoluted from the RTD of the entire system to obtain the RTD of TBC alone. This novel technique is not available in the literature and it can also eliminate the problem of location of the probe.

In the presence of downcomer, the liquid discharge is through the downcomer only, and does not allow liquid to flow through the supporting grid across the cross-section. Under these conditions, the exit concentration of the tracer can be measured more accurately by placing a probe in the downcomer.

3.4.1. Deconvolution method

All the RTD data obtained for TBC with MFT and empty column (without solids) with MFT are used to obtain the RTD of TBC alone by deconvolution. This ensures the

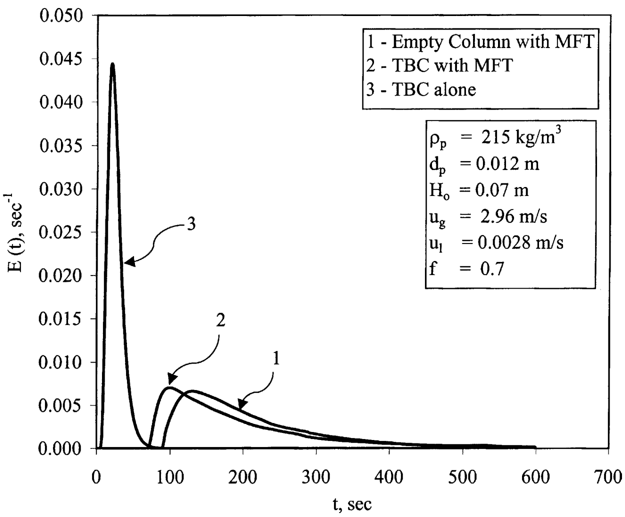

Fig. 11. RTD curves for empty column with MFT, TBC with MFT and TBC alone.

subtraction of all the delays in the system. The convolution integral equation is given by

$$E_{\text{out}}(t) = \int_0^t f(\tau, Pe) E_{\text{in}}(t - \tau)\,\mathrm{d}\tau \tag{10}$$

where $E_{\text{out}}(t)$ is the smoothened data for TBC with MFT, $E_{\text{in}}(t)$ the smoothened RTD data for empty column with MFT, $f(\tau, Pe)$ the axial dispersion model impulse response function of TBC alone and $\theta = [t/\tau]$ is the dimensionless residence time of the system.

The optimal value of the parameters Pe and τ are obtained by least square minimization of objective function (using the function 'leastsq' in MATLAB®)

$$J = \sum (E_{\text{out}} - E_{\text{outpred}})^2. \tag{11}$$

The asymptotic solutions developed by Brenner [21], for axial dispersion model with closed–closed boundary conditions and modified by Bruce et al. [14] were used for deconvolution. The detail of this method were presented in [14].

A typical figure with RTD of empty column with MFT, TBC with MFT and "TBC alone" is shown in Fig. 11. The mean residence time $\bar{t}$ of liquid phase obtained from RTD can be used to estimate the dynamic holdup of liquid in the bed from the equation

$$\varepsilon_{\text{l}} = \frac{\bar{t} Q_{\text{l}}}{SH} - 0.02 \tag{12}$$

where the second term on the right-hand side of Eq. (12) represents the volume fraction of liquid adhering to the particles per unit volume of the static bed and is independent of particle diameter and is accepted in the literature [3,4,6].

The liquid holdup estimated through RTD studies is compared with the liquid holdup obtained by hydrodynamics studies in Fig. 12, which compares within a RMS error of 25%.

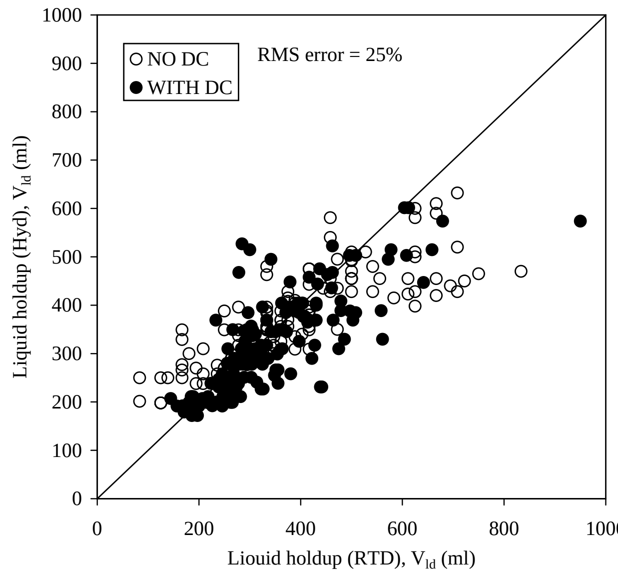

Fig. 12. Comparison of experimental and predicted liquid holdup.

The liquid holdup in TBC can be estimated either by measuring the pressure drop across the bed, collecting liquid by simultaneous shutting off flow of gas and liquid phases or RTD studies. Of these three methods pressure drop method underestimates the liquid holdup, since the concept of equating the pressure drop across the bed to the weight per unit area of the liquid and particles does not hold good. This is due to, not all the liquid in the bed is supported by the upward flow of gas in the column. The RTD method may also not give accurate estimation of liquid holdup due to small residence times associated with the liquid phase. Considerable experimental difficulties have to be faced if the mean residence time of a phase is small. The estimation of liquid holdup through collection method seems to be more accurate. However, considerable instrumentation is required for this method.

4. Conclusions

Four modes of TBC operations, viz. Type I TBC with and without downcomer, and Type II TBC with and without downcomer are used and data are collected on liquid holdup. Correlations are developed for dynamic liquid holdup for four modes of operations with a maximum error of 18%. The error involved in the estimation of liquid holdup through RTD studies seems to be higher than the collection method.

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