Hydrodynamic aspects of multi-stage turbulent bed contactor

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The hydrodynamic behaviour in each stage of multi-stage Turbulent Bed Contactor operations has been studied for light (Type I) and dense (Type II) particles. The experimental data are collected on dynamic liquid holdup, gas holdup, bed expansion and bed pressure drop across each stage for operating parameters such as superficial gas and liquid velocities, particle characteristics, geometric parameters of the column such as static bed height, free-open area of the supporting grid, distance between the supporting grids, downcomer diameter and weir height. In multi-stage operation, it was experimentally observed that the hydrodynamic behaviour of each stage corresponds to a single-stage behaviour. In single-stage TBC for Type I and Type II operations, liquid holdup increases with increase in velocities of gas and liquid and particle density and with decrease in free-open area, diameter of particle and static bed height. Gas holdup increases with increase in gas velocity and with decrease in free-open area. Correlations for liquid and gas holdups have been proposed based on the experimental data. Bed expansion and bed pressure drop are calculated using gas and liquid holdups.

A Turbulent Bed Contactor (TBC) employs three-phase fluidization with gas flowing upward as the continuous phase and the liquid is sprayed countercurrently from the top. It is an efficient device capable of contacting liquid and particulate-laden gas at large throughputs without plugging. It has immense potential for scrubbing, absorption and pollution control. It can be operated as Type I or Type II operation depending on the density of the particles. In Type I TBC operation, light particles less than about 300 kg/m³ are used and the minimum fluidization velocity is attained at a gas velocity lower than the flooding velocity for the equivalent countercurrent packed bed. Whereas in Type II TBC operation, denser particles greater than about 300 kg/m³ are used and the minimum fluidization velocity is attained at the flooding point. The flooding point here refers to the condition where all the interstices of the packed bed are filled with liquid which is the upper limit of operation of a conventional packed bed. TBC operation is impossible if the density of the particles exceeds 1300 kg/m³. The successful design and operation of a TBC depends on the hydrodynamics, the mixing of the phases, and the heat and mass transfer characteristics. The present work is limited to the hydrodynamic characteristics of multi-stage TBC alone on which the literature has little information.

In TBC operation, non-uniform fluidization behaviour such as channelling and backmixing of the liquid phase, by-passing of the gas phase and slugging may be present. Backmixing of the phases is brought mainly by the vigorous motion of the particles which reduces the concentration and temperature gradients. Sometimes, it may be necessary to have axial concentration and temperature gradients. Under these conditions, one has to resort to multi-stage operation of TBC. Apart from this, the other advantages of multi-stage operation are—

(i) reduction in the axial mixing of the fluid phases with possible uniform quality of the product, (ii) higher rates of chemical reaction compared to the single-stage, (iii) reduction in the overall size of the process equipment for identical production rates, and (iv) reduction or minimizing channelling of the liquid phase, bypassing of the gas phase and slugging in deep beds.

For deep static beds, normally with $H_d/D_i >> 1$, slugging may be encountered. By distributing the particles over several shallow beds in multi-stage TBC, slugging can be avoided. It was reported that the total liquid volume in the TBC decreases with
increasing static bed height and there is an optimum performance for the given volume of packing with the available pressure drop.

Numerous correlations are available in the literature on the hydrodynamics of single-stage TBC\(^4\). Relatively little information is available on the hydrodynamics of a multi-stage TBC operation\(^5\)-\(^8\). Very few investigators dealt with the study of multi-stage operations exclusively. Only Kito et al.\(^7\) studied the pressure drop and holdups of gas and liquid in multi-stage TBC operation while others just mentioned the pressure drop measurements. Without any fundamental work, multi-stage TBC columns are mentioned in the literature for the following applications: (i) removal of SO\(_2\) from flue gases\(^9\) and (ii) rectification of alcohol-water mixture\(^10\). Thus, it can be seen that very little information is available on the hydrodynamics of multi-stage TBC either in Type I or Type II operation. Hence, in the present work, experimental data are collected for phase holdups, bed expansion and pressure drop for multi-stage Type I and Type II TBC and correlations are proposed.

**Experimental Procedure**

The schematic diagram of the experimental setup is shown in Fig. 1. The test section consisted of a Perspex column of 113 mm in diameter and with multiple sections. The height of each stage was 305 mm. The total height of the column including the collection tank at the bottom was 2.5 m. In the present work, two and three stages were used to collect the experimental data. The supporting grids of same free-open area were used for each stage. The distance provided between the grids was sufficient to have adequate free-board between the stages to avoid instant flooding.

The gas (air) was sent from the bottom of the column to fluidize the particles and the liquid (water) was sprayed countercurrently from the top. The liquid flow rate was measured by means of rotameters, while the gas flow rate was measured by using rotameters or an orifice meter. The pressure drop across the bed was measured using U-tube manometers. In a typical experiment in multi-stage TBC operation, to obtain pressure drop, phase holdups and bed expansion, a particular free-open area of the supporting grid, static bed height, size and density of the particle were chosen. 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 bed height was noted along with pressure drop across the bed and liquid level in the collection tank. The bed height was measured by visual observation from all sides of the column and averaging the fluctuations. 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. The volume of the liquid collected in the collection tank is measured which corresponds to the dynamic liquid holdup. Using these values, the holdups of the phases can be calculated. This procedure was repeated for a wide range of experimental conditions. The range of parameters studied in the present work are given in Table 1. The details of the perforated grids and the characteristics of the particles are given in Tables 2 and 3, respectively.

**Results and Discussion**

Extensive experimental data have been collected\(^11\) over a wide range of variables for liquid and gas holdups, bed expansion and bed pressure
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Fig. 2—Comparison of dynamic liquid holdup in each stage of three-stage Type I TBC. \( U_G = 0.0054 \text{ m/s}, \ d_p = 0.0125 \text{ m}, \ \rho_p = 243 \text{ kg/m}^3, \ f = 0.521, \ H_v = 0.085 \text{ m}, \ H_m = 0.305 \text{ m}, N = 3 \)

Fig. 2 is a typical representation of dynamic liquid holdup data across each stage of three-stage Type I TBC. It can be seen that there is not much variation in the holdup data of each stage in multi-stage TBC. Thus, the liquid holdup in each stage of multi-stage TBC is similar to that of single-stage TBC. In a single-stage TBC, it is experimentally observed that the dynamic liquid holdup based on static bed volume increases with increase in liquid and gas velocities, density of the particles and with decrease in free-open area, diameter of the particle and static bed height. Similar observations are also reported by several other workers. Kito et al. also observed the same phenomenon. Since each stage in multi-stage operation behaves like a single-stage TBC, the correlation for dynamic liquid holdup in a single-stage TBC represents the data in multi-stage TBC. The correlation is given as,

\[ \varepsilon_{lit,d} = 9.5 \frac{H_v}{d_p} \left( \frac{d_f}{D_e} \right)^{0.58} \left( \frac{d_f}{D_e} \right)^{0.55} \]  

Fig. 3 compares the experimental dynamic liquid holdup obtained in each stage of multi-stage operation with the correlation proposed [Eq. (4)]. The experimental liquid holdup data for single-stage operation also fit with the correlation satisfactorily. The data are found to fit with the correlation with a mean relative error of \( \pm 33 \% \).

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### Table 1—Range of Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_G ) (m/s)</td>
<td>0 - 3</td>
</tr>
<tr>
<td>( U_d ) (m/s)</td>
<td>0 - 0.032</td>
</tr>
<tr>
<td>( H_v ) (m)</td>
<td>0.113, 0.17, 0.226, 0.255, 0.34 and 0.51</td>
</tr>
<tr>
<td>( f )</td>
<td>0.155, 0.25, 0.349, 0.521 and 0.728</td>
</tr>
<tr>
<td>( d_p ) (m)</td>
<td>0.012, 0.0125, 0.0158, 0.016, 0.02 and 0.025</td>
</tr>
<tr>
<td>( \rho_p ) (kg/m(^3))</td>
<td>110, 116.7, 122, 243, 599, 870 and 995</td>
</tr>
<tr>
<td>( H_m ) (m)</td>
<td>0.305, 0.61, 0.915 and 1.22</td>
</tr>
</tbody>
</table>

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### Table 2—Details of the perforated grids

<table>
<thead>
<tr>
<th>Number of perforations</th>
<th>Triangular pitch, ( d_p ) (mm)</th>
<th>( f )</th>
<th>( D_e ) (m)</th>
<th>( f_d/D_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>7</td>
<td>0.0030</td>
<td>0.155</td>
<td>0.0445</td>
</tr>
<tr>
<td>158</td>
<td>7</td>
<td>0.0045</td>
<td>0.250</td>
<td>0.0565</td>
</tr>
<tr>
<td>55</td>
<td>14</td>
<td>0.0090</td>
<td>0.349</td>
<td>0.0668</td>
</tr>
<tr>
<td>55</td>
<td>14</td>
<td>0.0110</td>
<td>0.521</td>
<td>0.0816</td>
</tr>
<tr>
<td>55</td>
<td>14</td>
<td>0.0130</td>
<td>0.728</td>
<td>0.0964</td>
</tr>
</tbody>
</table>

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Type I TBC

**Liquid holdup**—The dynamic liquid holdup data for multi-stage TBC are experimentally obtained by collecting the total volume of liquid. The liquid holdup for each stage is calculated by dividing the total volume of liquid collected in the same proportion as that of the pressure drop ratio of that particular stage. However, the experimentally measured pressure drop across each stage is approximately the same suggesting that the liquid holdup in each stage is almost equal within the experimental limitations. The total liquid holdup \( \varepsilon_L \) is the sum of the dynamic liquid holdup and the static liquid holdup. The static liquid holdup is the amount of liquid adhering to the particles and is measured by weighing the wetted particles after the flow of the phases is stopped. The static liquid holdup based on packed bed volume is experimentally measured as

\[ \varepsilon_{lit,stat} = 0.02 \text{ m}^3/\text{m}^3 \]  

which represents the volume of liquid adhering to the particles per unit volume of static (packed) bed which is accepted in the literature. For accurate estimation of dynamic liquid holdup, calculations are based on static bed height as

\[ \varepsilon_{lit,d} = \varepsilon_{lit,stat} \frac{H}{H_v} \]  

where

\[ \varepsilon_{lit} = \varepsilon_{lit,d} \frac{V_{lit}}{SH} \]

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Fig. 3—Comparison of dynamic liquid holdup obtained in each stage of multi-stage TBC. Some of the typical results are presented here.
Table 3—Characteristics of the particles

<table>
<thead>
<tr>
<th>Nature of the particles</th>
<th>( d_p ) (m)</th>
<th>( \varepsilon_p ) (m(^2)/m(^3))</th>
<th>( \rho ) (kg/m(^3))</th>
<th>Type of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth and hollow, polypropylene spheres with equatorial ring</td>
<td>0.0125</td>
<td>0.414</td>
<td>243.0</td>
<td>Type I</td>
</tr>
<tr>
<td>Smooth and hollow, polypropylene spheres with equatorial ring</td>
<td>0.016</td>
<td>0.420</td>
<td>116.7</td>
<td>Type I</td>
</tr>
<tr>
<td>Smooth and hollow, polypropylene spheres with equatorial ring</td>
<td>0.020</td>
<td>0.428</td>
<td>122.0</td>
<td>Type I</td>
</tr>
<tr>
<td>Smooth and hollow, polypropylene spheres with equatorial ring</td>
<td>0.025</td>
<td>0.430</td>
<td>110.0</td>
<td>Type I</td>
</tr>
<tr>
<td>Smooth and hollow, polypropylene spheres with equatorial ring</td>
<td>0.0125</td>
<td>0.414</td>
<td>599.0</td>
<td>Type II</td>
</tr>
<tr>
<td>Smooth and solid, polypropylene spheres with equatorial ring</td>
<td>0.012</td>
<td>0.408</td>
<td>870.0</td>
<td>Type II</td>
</tr>
<tr>
<td>Spherical, plastic bead</td>
<td>0.0158</td>
<td>0.464</td>
<td>995.0</td>
<td>Type II</td>
</tr>
</tbody>
</table>

The mean relative error is calculated using the equation.

\[
\sigma_r = \sqrt{\frac{\sum_{i=1}^{n} \frac{X_{\text{calc},i} - X_{\text{exp},i}}{X_{\text{exp},i}}^2}{n-1}} \tag{5}
\]

Gas holdup—The gas holdup is estimated from the equation

\[
\varepsilon_G = 1 - (\varepsilon_L + \varepsilon_P) \tag{6}
\]

where,

\[
\varepsilon_L = \frac{V_L}{S \cdot H} \tag{7}
\]

\[
\varepsilon_P = \frac{V_P}{S \cdot H} = \left(1 - \varepsilon_o \right) \frac{H_o}{H} \tag{8}
\]

The gas holdup in each stage is determined using the present experimental liquid holdup and bed expansion data for two- and three-stage TBC. Fig. 4 shows the comparison of gas holdup across each stage of three-stage Type I TBC and are found to be almost equal. This suggests that each stage of multi-stage TBC behaves like a single-stage TBC. In a single-stage TBC, it is experimentally observed that the gas holdup increases with increase in gas velocity and is almost independent of particle density, free-open area, static bed height, liquid velocity and the perforation diameter of the supporting grid. In the present work, low free-open areas of the supporting grid are used and this may be the reason for increase in gas holdup with decrease in free area. The correlation for gas holdup is,

\[
\varepsilon_G = 0.149 \left( \frac{W_{G}}{W_{G}}^* \right)^{0.11} \left( \frac{F_{G}}{F_{G}}^* \right)^{0.22} \tag{9}
\]

Eq. (9) is used to correlate the experimental gas holdup data obtained from each stage of multi-stage operation. The experimental gas holdup data of Kito et al.\(^1\) for single-stage operation also fit with the correlation satisfactorily. It can be seen from Fig. 5 that the data are found to fit with the correlation with a mean relative error of ± 13 %.

Bed expansion—The expanded bed height for each stage of multi-stage Type I TBC is measured by visual observation and the fluctuations are averaged. It is experimentally found that the variation in bed height with system variables is similar to single-stage TBC which shows that the bed height increases with increase in liquid and gas velocities and with decrease in free-open area. Bed expansion can be estimated using the correlations
the equation can be derived to estimate the bed expansion as,

\[
\frac{H}{H_0} = \frac{(1 - \varepsilon_g) + (\varepsilon_{L,\text{st}} + 0.02)/(1 - \varepsilon_g)}{\varepsilon_g} \quad \ldots \quad (10)
\]

where \(\varepsilon_{L,\text{st}}\) and \(\varepsilon_g\) are given by Eqs (4) and (9), respectively. Fig. 6 compares the experimental data for multi-stage TBC with the correlation proposed for single-stage TBC satisfactorily with a mean relative error of ± 15.7 %.

**Pressure drop**—The total pressure drop across each stage in a multi-stage TBC is measured from which the frictional pressure drops due to the grids and the wall of that particular stage are subtracted to obtain bed pressure drop of that stage. Experimentally, it is observed that the bed pressure drop in each stage is almost the same (Fig. 7) which confirms the behaviour of each stage in a multi-stage TBC similar to a single-stage TBC. The pressure drop across each stage increases with increase in gas and liquid velocities, particle density and static bed height and with decrease in free-open area of the supporting grid. Pressure drop across each stage can be calculated using the liquid holdup correlation Eq. (4) without proposing a new correlation for the pressure drop. From the basic
The overall pressure drop for three-stages increases slightly with increase in gas velocity, as shown in Fig. 7. The variation in pressure drop with process variables is also similar to a single-stage TBC. Eq. (11) is used to characterize the experimental data in terms of the friction factor defined earlier\textsuperscript{15} as,

\[ \psi = \left( \frac{-\Delta P}{(4 n_p \rho U_0^2 / D_p)} \right) \left( \frac{D_e}{d_p} \right)^2 \quad \ldots (12) \]

Eqs (11) and (12) have been used to correlate the multi-stage data. Fig. 8 compares the experimental and the calculated friction factors for single-, two- and three-stage TBC within a mean relative error of \( \pm 29.5\% \).

**Type II TBC**

The behaviour of multi-stage Type II TBC is presented here with respect to liquid and gas holdup, bed expansion and pressure drop.

**Liquid holdup**—Type II TBC is associated with high turbulence due to the presence of dense particles. Since dynamic liquid holdup depends on bed height measurement [Eq. (3)], the bed height is measured very carefully as follows. After the steady state is attained, the bed fluctuations are noted for at least 10 to 15 min from all sides of the column and the average of these observations is taken as the bed height. The liquid holdup for each stage is calculated using the total liquid holdup in the same proportions as that of bed pressure drop of each stage.

It is observed experimentally that each bed has approximately the same pressure drop which corresponds to almost the same liquid holdup in the bed. This suggests that each stage of multi-stage TBC behaves as a single-stage TBC even in Type II operation. The liquid holdup in a single-stage of Type II TBC varies with operating parameters similar to Type I TBC (Section A). Based on the experimental data, the following correlation is proposed for dynamic liquid holdup,

\[ \varepsilon_{l, d, e} = 7.705 (H_o / d_p)^{0.2} (d_e / D_e)^{0.58} \]

\[ Ga^{0.09} Fr^{0.66} Re^{-0.34} We^{0.34} (U_o)^{0.57} \quad \ldots (13) \]

Fig. 9 compares the experimental dynamic liquid holdup in each stage of two- and three-stage Type II TBC operations with the proposed correlation [Eq. (13)]. The dynamic liquid holdup data...
obtained earlier\textsuperscript{13,16} also fit with the present correlation satisfactorily. The data fit with the correlation with an error of ±22%.

Gas holdup—Experimental observation suggests that the gas holdup in each stage is identical in all stages. The gas holdup in each stage increases with increase in gas velocity and with decrease in free-open area. Based on the experimental data, a correlation for gas holdup is proposed as,

\[
\varepsilon_g = 0.76 (We_\text{e}^+)^{0.11} (Fr_\text{e}^-)^{0.22} d_{\text{p}}^{-0.37} 
\]  \hspace{1cm} (14)

Fig. 10 compares the experimental gas holdup obtained in each stage of multi-stage TBC with the proposed correlation. In Fig. 10, the experimental gas holdup data of Kito \textit{et al.}\textsuperscript{13} and Vunjak-Novakovic \textit{et al.}\textsuperscript{16} for single-stage TBC operation are also shown. The literature data shown in the figure is not fitting satisfactorily which may be due to the tremendous turbulence that is characteristic of Type II operation. The deviation is also attributed to the inclusion of perforation diameter in the present correlation.

Bed expansion—The bed expansion data are carefully measured as explained in Type II TBC (Section A). From the experimental data, it is seen
that the bed expansion increases with increase in gas and liquid velocities and with decrease in free-open area. Since the bed expansion is almost the same in each stage, the bed expansion can be estimated using Eqs (10), (13) and (14). Fig. 11 compares the experimental and the calculated bed expansion data for each stage in two-stage and three-stage operations.

Pressure drop—it is generally expected that the pressure drop in Type II TBC is greater than that of Type I TBC since denser particles are used in the former. The pressure drop across each bed fluctuates because of the characteristic nature of Type II TBC and care is taken to minimize the error by observing fluctuations over a period of time and averaging. The pressure drop across each stage of three-stage Type II TBC is almost identical as observed experimentally. The pressure drop can be estimated using Eqs (11) and (13). In terms of friction factors \[ \text{Eq. (12)} \], Fig. 12 compares the experimental and the calculated data for single-, two- and three-stage operations satisfactorily with a mean relative error of ±24.3%.

Conclusions
Based on experimental data, the conclusions drawn for multi-stage Type I and Type II TBC operations are,

(i) the hydrodynamic behaviour with respect to liquid and gas holdups, bed expansion and bed pressure drop in each stage is almost similar,
(ii) the liquid holdup increases with increase in gas and liquid velocities and particle density and with decrease in free-open area, particle size and static bed height,
(iii) The gas holdup increases with increase in gas velocity and with decrease in free-open area, and
(iv) Bed expansion and bed pressure drop can be estimated using basic Eqs (10) and (11) in terms of phase holdups correlations.

Nomenclature

- \( d_{eq} \) = equivalent diameter of the free-opening of the supporting grid, m
- \( d \) = diameter of the particle, m
- \( D \) = diameter of the column, m
- \( D_{eq} \) = equivalent diameter for the free-open area of the supporting grid, m
- \( f \) = fractional free-open area of the supporting grid, -
- \( Fr_{g} \) = Modified Froude number for gas phase \( U_{g}/(gd_{p})^{0.5} \), -
- \( Fr_{l} \) = Froude number for liquid phase \( U_{l}/(gd_{p})^{0.5} \), -
- \( g \) = acceleration due to gravity, 9.807 m/s²
- \( Ga_{l} \) = Galileo number for liquid phase \( d_{p}^{3} \rho_{p}^{2}/\mu_{l}^{3} \), -
- \( H \) = height of the expanded bed, m
- \( H_{s} \) = static bed height, m
- \( H_{m} \) = distance between the supporting grid and the retaining mesh, m
- \( n \) = number of particles
- \( N \) = number of stages
- \( \Delta P \) = bed pressure drop, Pa
- \( Re_{l} \) = Reynolds number for liquid phase \( d_{p}U_{l}/\mu_{l} \), -
- \( S \) = cross-sectional area of the empty column, m²
- \( U_{g} \) = superficial gas velocity, m/s
- \( U_{l} \) = gas velocity at the perforation, m/s
- \( V_{l} \) = total volume of liquid in the bed, m³
- \( V_{s} \) = volume of solid in the bed, m³
- \( W_{r} \) = Modified Weber number for gas phase \( d_{p}U_{g}^{2}/\rho_{l}\sigma_{g} \), -
- \( W_{r} \) = Weber number for liquid phase \( d_{p}U_{l}^{2}/\rho_{l}\sigma_{l} \), -
- \( X_{calc} \) = calculated value
- \( X_{exp} \) = experimental value

Greek letters

- \( \varepsilon \) = voidage of the static bed without gas-liquid flow, m³/m³
- \( \varepsilon_{eq} \) = gas holdup or \( V_{g}/(SH) \), m³/m³
- \( \varepsilon_{l} \) = liquid holdup or \( V_{l}/(SH) \), m³/m³
- \( \varepsilon_{d,L} \) = dynamic liquid holdup based on static bed volume, m³/m³
- \( \varepsilon_{p} \) = solid holdup or \( V_{p}/(SH) \), m³/m³
- \( \mu_{l} \) = viscosity of the liquid, Pa·s
- \( \rho \) = density of the gas, kg/m³
\[ \rho_l = \text{density of the liquid, kg/m}^3 \]
\[ \rho_p = \text{density of the particle, kg/m}^3 \]
\[ \sigma_s = \text{surface tension, N/m} \]
\[ \sigma_r = \text{mean relative error defined in Eq. (2)} \]
\[ \varphi = \text{friction factor defined in Eq. (9)} \]

References