Pressure drop and phase holdups in multi-stage turbulent bed contactor with downcomers

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Received 26 May 1997; accepted 10 June 1998

Downcomers are provided to each stage in Turbulent Bed Contactor (TBC) to extend the flooding limit and operating range. Experimental study has been undertaken to model the hydrodynamic behaviour of multistage Type I and Type II Turbulent Bed Contactor with downcomer attachment. Extensive data for various operational parameters including dynamic liquid hold-up, gas hold-up and bed pressure drop across each stage in the Turbulent Bed Contactors are obtained and empirical correlations are proposed.

A Turbulent Bed Contactor (TBC) is a countercurrent three-phase fluidized bed with gas usually serving as the continuous phase and liquid as the dispersed phase. Inert particles are used to enhance the contact between the flowing fluid phases. This efficient gas-liquid contacting device can simultaneously treat polluted gases and particulates at large throughputs. A TBC has been used for physical, chemical and biochemical processing. In physical processing, it is used for air cooling, humidification or dehumidification, particulate removal and lactose granulation. In chemical processing, it has tremendous potential for flue gas desulfurization, absorption, scrubbing, desorption and distillation. In biochemical processing, it is used for alcohol fermentation.

O'Neill et al. classified TBC operation as Type I and Type II operation. In Type I TBC operation, low density particles less than about 300 kg/m³ are used and the onset of fluidization occurs at a gas velocity lower than the flooding point for the equivalent countercurrent packed bed. In Type II TBC operation, particles with a density greater than about 300 kg/m³ are used and the onset of fluidization occurs at the flooding point. The flooding point here refers to the state in which the entire voidage of the packed bed is filled with liquid which corresponds to the upper bound of operation of a conventional packed bed. TBC operation is not possible if the particle density exceeds 1300 kg/m³.

A TBC can also be operated with small free-open areas. Small free-open areas cause accumulation immediately above the supporting grid. A serious drawback in such a system is the attainment of spontaneous flooding which limits the capacity of the column. Provision of a downcomer (DC) to route the liquid through it to the stage down helps in extending the flooding limit and increases the gas-treating capacity of the column. No information is available in the literature on the hydrodynamic characteristics of a TBC with DC.

In a single-stage TBC operation with downcomer, drawbacks like channelling and backmixing of the liquid phase and by-passing of the gas phase may be present. Such deleterious effects can be overcome or minimized by operating it as a multi-stage TBC with downcomers. Besides, slugging can be avoided. No information is available in the literature on the hydrodynamic characteristics of a multi-stage TBC operation with DC. The objective of the present work is to collect experimental data on hydrodynamic aspects such as pressure drop, liquid and gas holdups for multi-stage Type I and Type II TBC with downcomers and to propose correlations.

Experimental Procedure
A schematic diagram of three-stage TBC with downcomers is shown in Fig. 1. The column was
made of Perspex with an ID of 113 mm using multiple sections. The height of each section (stage) was 305 mm and the total height of the column including the collection tank was 2.5 m. The downcomers were fixed to the supporting grids with identical free-open area for two- and three-stage TBC operation. A typical illustration of the downcomer is shown in Fig. 2. Each downcomer 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 fluidized bed in multi-stage operation. A rigid wire was tied across the mouth of each downcomer in order to prevent the particles from entering it. Air was fed at the bottom of the column and exited at the top. Water was pumped from the storage tank and sprayed from the liquid distributor, countercurrent to the upflowing air. Under steady state conditions, the pressure drop across the bed was measured using U-tube manometers and the expanded bed height was measured by visual observation. The liquid holdup was measured by collecting the liquid after the simultaneous shut-off of gas and liquid flow. Experiments were conducted on two- and three-stage TBC with downcomers to collect the data on dynamic liquid holdup, gas holdup and bed pressure drop over a wide range of process variables. The range of parameters studied are given in Table 1. The details of the perforated grids and the characteristics of the particles used are given in Tables 2 and 3, respectively.

Results and Discussion

Multi-stage TBC operation with DC may be preferred for operations like absorption and
Table 2—Details of the perforated grids

<table>
<thead>
<tr>
<th>Number of perforations</th>
<th>Triangular pitch, mm</th>
<th>$d_p$ m</th>
<th>$f$ (-)</th>
<th>$D_t$ m</th>
<th>$fL/D_t$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>7</td>
<td>0.0030</td>
<td>0.155</td>
<td>0.0445</td>
<td>0.01045</td>
</tr>
<tr>
<td>158</td>
<td>7</td>
<td>0.0045</td>
<td>0.250</td>
<td>0.0565</td>
<td>0.01991</td>
</tr>
<tr>
<td>55</td>
<td>14</td>
<td>0.0090</td>
<td>0.349</td>
<td>0.0668</td>
<td>0.04705</td>
</tr>
<tr>
<td>55</td>
<td>14</td>
<td>0.0110</td>
<td>0.521</td>
<td>0.0816</td>
<td>0.07026</td>
</tr>
<tr>
<td>55</td>
<td>14</td>
<td>0.0130</td>
<td>0.728</td>
<td>0.0964</td>
<td>0.09816</td>
</tr>
</tbody>
</table>

Table 3—Characteristics of the particles

<table>
<thead>
<tr>
<th>Nature of the particles</th>
<th>$d_p$ m</th>
<th>$e_0$ m$^3$/m$^3$</th>
<th>$\rho_p$ 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>

rectification. Staging the column improves the concentration and temperature gradients and reduces channelling of the liquid, by-passing of the gas and slugging of the bed. Extensive data are collected over a wide range of variables for two- and three-stage TBC with DC on liquid and gas holdups, and bed pressure drop for Type I and Type II TBC operations. Typical data are presented here.

Type I TBC with DC

Liquid holdup—The dynamic liquid holdup data are experimentally determined by collecting the total volume of liquid in all the stages. The liquid holdup in 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. Experimentally, the pressure drop measured across each stage is approximately the same. This suggests that the liquid holdup in each stage is almost the same. The static liquid holdup $\varepsilon_{L, st}$ which is due to the liquid upheld by adhesive forces on the particles, when subtracted from the total liquid holdup $\varepsilon_L$ in a TBC will give the dynamic liquid holdup $\varepsilon_{L, d, st}$. The static liquid holdup is obtained by weighing the wetted particles after the shutting-off of gas and liquid flow and subtracting it with the weight of dry particles.

$$\varepsilon_{L, st} = 0.02 \text{ m}^3/\text{m}^3$$  \hspace{1cm} ... (1)

This value, which represents the volume of liquid adhering to the particles per unit volume of static bed, is accepted. Dynamic liquid holdup can be accurately estimated if the calculations are based on static bed volume as

$$\varepsilon_{L, d, st} = \varepsilon_{L, d} H / H_0$$  \hspace{1cm} ... (2)

where

$$\varepsilon_{L, d} = V_{L, d} / SH$$  \hspace{1cm} ... (3)

From the experimental data, it can be observed that the dynamic liquid holdup increases with increase in gas and liquid velocities and weir height, and with decrease in free-open area, diameter of the particles, static bed height and diameter of the DC. The same
trends are also observed for single-stage operation with DC. It is also observed that there is not much variation in the dynamic liquid holdup in each stage of two-stage or three-stage operation with DC. This can be seen from Fig. 3. Thus, liquid holdup in each stage of multi-stage TBC with DC is close to that of single-stage TBC with DC. Hence, the correlation proposed for dynamic liquid holdup for single-stage Type I TBC with DC can be used to correlate the data for each stage in multi-stage operation and the total holdup in a multi-stage TBC with DC can be obtained by multiplying the holdup with the corresponding number of stages. The correlation [Eq. (4)] proposed for dynamic liquid holdup in single-stage for Type I TBC with DC is\(^7\)

\[
\varepsilon_{L,d,st} = 0.0596 U_L^{0.105} d_p^{-0.33} (S_d / D_c)^{-0.5} H_0^{-0.5} \\
+ d_{DC}^{-0.51} h_w^{0.125} (U_G^*)^{0.5} 
\]

... (4)

This correlation is compared with the experimental dynamic liquid holdup data in each stage of two- and three-stage operations as shown in Fig. 4 with a mean relative error of \(\pm 21.6\%\). The mean relative error is calculated using Eq. (5).

\[
\sigma_r = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left( \frac{X_{calc,i} - X_{expt,i}}{X_{expt,i}} \right)^2} \quad \text{... (5)}
\]

**Gas holdup**—From the measured values of bed expansion and liquid holdup for each stage of two- and three-stage operation, gas holdup can be calculated as

\[
\varepsilon_G = 1 - (\varepsilon_L + \varepsilon_p) 
\]

... (6)

where

\[
\varepsilon_L = V_L / S_H 
\]

... (7)

and

\[
\varepsilon_p = V_p / S_H = (1 - \varepsilon_G) H_a / H 
\]

... (8)

From the experimental data, it is observed that the gas holdup mainly depends on gas velocity at the perforation and to some extent on perforation diameter. Fig. 5 compares the gas holdup in each stage of three-stage operation and it is found that the gas holdup in each stage is almost the same. This suggests that each stage of multi-stage TBC behaves like a single-stage operation. The correlation [Eq. (9)] proposed for gas holdup in single-stage for Type I TBC with DC is\(^7\)

![Fig. 3—Comparison of dynamic liquid holdup in each stage of three-stage Type I TBC with DC.](image)

![Fig. 4—Comparison of experimental dynamic liquid holdup obtained in multi-stage operation with the correlation proposed for a single-stage Type I TBC with DC.](image)
Eq. (10) assumes that the contribution to the pressure drop is mainly due to the weight of the dry packing and the dynamic liquid holdup. Eq. (10) is used to characterize the experimental data in terms of friction factor defined by Brauer and Varma as

$$\psi = \frac{(-\Delta P_B)}{(4 n_p \rho_G U_G^2)} \left( \frac{D_C}{d_p} \right)^2 \quad \cdots (11)$$

Fig. 8 compares the experimental and the calculated friction factors satisfactorily for single-, two- and three-stage Type I TBC with DC with a mean relative error of $\pm 19.3\%$.

**Type II TBC with DC**

Experimental data are collected on dynamic liquid holdup, gas holdup and bed pressure drop for two- and three-stage TBC operation.

**Liquid holdup**—The dynamic liquid holdup data are experimentally determined in a similar way as observed for Type I TBC with DC. It is also observed that each stage in two-stage or three-stage operation behaves as a single-stage operation with respect to liquid holdup. It is found from experimental data that, as in single-stage operation, the liquid holdup in each stage of multi-stage TBC increases with increase in gas and liquid velocities, particle density, weir height of the DC and with decrease in free-open area, particle size and diameter of the DC. The correlation proposed for dynamic liquid holdup in single-stage for Type II TBC with DC is:

$$\varepsilon_{L,\text{d,stat}} = 1.169 \times 10^{-5} U_G^2 \left( \frac{d_0}{D_C} \right)^{0.6} H_0^{0.2} \rho_p^{1.63} \frac{1}{d_{DC}^{-0.5}} h_w^{0.05} \left( \frac{U_G}{G} \right)^{0.5} \quad \cdots (12)$$
This correlation is used to compare the data obtained for liquid holdup in each stage of two- and three-stage Type II TBC with DC and the comparison is shown in Fig. 9.

Gas holdup—From the experimental data, it is observed that gas holdup in each stage of multi-stage is mainly a function of gas velocity at the perforation and to some extent, of particle size. It is also found that each stage in multi-stage operation is almost identical in behaviour, suggesting that each stage of multi-stage TBC behaves as a single-stage TBC. The correlation proposed by Soundarajan\(^7\) for gas holdup in single-stage for Type II TBC with DC is,

\[
\varepsilon_G = 0.322(Fr_G^*)^{0.22}
\]

Eq. (13) is used to correlate the data obtained in each stage of multi-stage TBC with DC. The experimental and the calculated gas holds in each stage are compared in Fig. 10 with a mean relative error of ± 25.4%.

Pressure drop—The bed pressure drop \(-\Delta P_B\) is measured across each stage of two- and three-stage TBC with DC. From the experimental data, it is seen that the pressure drop across each stage increases with increase in gas and liquid velocities, static bed height, density of the particles, weir height and with decrease in free-open area and downcomer diameter. Experimentally, it is observed that the pressure drop across each bed is almost the same in multi-stage operation and also similar to single-stage TBC with DC. Therefore, the equations proposed to predict the pressure drop for single-
Fig. 10—Comparison of experimental gas holdup obtained in multi-stage operation with the correlation proposed for a single-stage Type II TBC with DC.

Fig. 11—Comparison of experimental friction factor obtained in multi-stage operation with the friction factor calculated for a single-stage Type II TBC with DC.

Stage Type II TBC with DC, given by Eqs (10) and (12) are used. In terms of friction factor defined in Eq. (11), Fig. 11 compares the data for single-, two- and three-stage Type II TBC with DC satisfactorily with a mean relative error of ±11.8%.

A comparison of the overall bed pressure drop across three-stages for Type I and Type II operations with and without DC is illustrated in Fig. 12. As expected, the pressure drop in Type II TBC is greater than Type I TBC which is due to dense particles used. However, pressure drop is not a limitation when choosing this operation because of its excellent mass transfer characteristics due to intense agitation in a single-stage. For TBC operation with downcomers, the pressure drop in both types of operation is less when compared to the conventional TBCs. The other advantages identified with DC are,

(i) increase in gas-treating capacity of the column and

(ii) the possibility of operating in gas continuous regime (preferred regime in TBC operation) even with low free-open areas of the supporting grid.

Conclusion

From the experimental observations, it can be concluded that in general, each stage in two- and three-stage multi-stage TBC operation with DC behaves as a single-stage with respect to gas and liquid holdups, and bed pressure drop. This observation is true for Type I and Type II TBC operations.
In Type I operation, in any stage, dynamic liquid holdup increases with increase in gas and liquid velocities and weir height, and with decrease in free-open area, diameter of the particle, static bed height and diameter of the DC. The gas holdup in each stage increases with increase in gas velocity at the perforation and to some extent with the perforation diameter. The pressure drop across each stage increases with increase in gas and liquid velocities, static bed height, weir height of the DC, and with decrease in free-open area, particle size and downcomer diameter.

In Type II operation, in any stage, dynamic liquid holdup is observed to increase with increase in gas and liquid velocities and weir height, and with decrease in free-open area, static bed height and diameter of the DC. Gas holdup in each stage increases with increase in gas velocity at the perforation. Experimental data show that the bed pressure drop across each stage increases with increase in gas velocity at the perforation. Experimental data show that the bed pressure drop across each stage increases with increase in gas and liquid velocities, static bed height, density of the particles and weir height of the DC, and with decrease in free-open area and downcomer diameter.

Using the experimental data, correlations for dynamic liquid holdup, gas holdup and bed pressure drop have been proposed.

Nomenclature

- $d_o$ = equivalent diameter of free-opening of the supporting grid, m
- $d_p$ = diameter of the particle, m
- $d_{oc}$ = inner diameter of the downcomer, m
- $D_c$ = diameter of the column, m
- $D_{df}^{eq}$, m
- $f$ = free-open area of the supporting grid, m
- $F_{R_G}^{*}$ = Modified Froude number for gas phase $U_G^{*}/(gd_p)^{0.5}$
- $g$ = acceleration due to gravity, 9.807 m/s$^2$
- $h_w$ = weir height of the downcomer, m
- $H$ = height of the expanded bed, m
- $H_m$ = distance between the supporting grid and the retaining mesh, m
- $N_p$ = number of particles
- $N$ = number of stages
- $-\Delta P_s =$ bed pressure drop, Pa
- $S$ = cross-sectional area of the empty column, m$^2$
- $U_G$ = superficial gas velocity, m/s
- $U_G^*$ = gas velocity at the perforation $U_G/\sqrt{g}$, m/s
- $U_L$ = superficial liquid velocity, m/s
- $V_L$ = total volume of liquid in the bed, m$^3$
- $X_{cal}$ = calculated value
- $X_{exp}$ = experimental value

Greek letters

- $\varepsilon_c =$ voidage of the static bed without gas-liquid flow, m$^3$/m$^3$
- $\varepsilon_g =$ gas holdup or $V_g/(S H)$, m$^3$/m$^3$
- $\varepsilon_{li}$ = dynamic liquid holdup based on static bed volume, m$^3$/m$^3$
- $\rho_g$ = density of the gas, kg/m$^3$
- $\rho_l$ = density of the liquid, kg/m$^3$
- $\rho_p$ = density of the particle, kg/m$^3$
- $\alpha$ = mean relative error defined in Eq. (5)
- $\Psi$ = friction factor defined in Eq. (11)

References