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Liquid-phase backmixing in bubble columns, structured by introduction of partition plates

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Abstract

Installation of perforated sieve plates into a bubble column has the effect of introducing structure into an otherwise chaotic hydrodynamic behaviour. In this study, we focus on the reduction of backmixing of the liquid phase in compartmentalised bubble columns. Liquid-phase residence time distribution (RTD) measurements were carried out in bubble columns with diameters $D_T = 0.10$, 0.15 and 0.38 m with air–water system operating at superficial gas velocities of $U_G = 0.05$–0.4 m/s. Partition sieve plates with open areas of 18.6 and 30.7% were used in the studies. The measured data on RTD were interpreted in terms of an axial dispersion model extended to allow for liquid interchange between compartments. The interchange velocity was found to be strongly dependent on the free area of the plates but practically independent of the column diameter.

Keywords: Bubble columns; Churn-turbulent flow regime; Partition; Backmixing; Liquid exchange

1. Introduction

Bubble columns slurry reactors are gaining increasing importance in view of the many applications in technologies for conversion of natural gas to liquid transportation fuels [1–9]. A distinguishing feature of the bubble column slurry reactor is the intense backmixing of the liquid phase. Published experimental studies on liquid-phase backmixing in bubble columns [10–12] have shown that the axial dispersion coefficient increases, significantly, with increasing column diameter, D_T. The liquid phase in a commercial-scale bubble column reactor say with $D_T = 6$ m can be considered to be completely backmixed. In a recent study, Maretto and Krishna [13] have stressed the advantages of introducing staging in the liquid phase by means of partition plates and have shown that significant improvements in reactor productivity can be achieved for the Fischer–Tropsch process. Use of partition plates introduces some "structure" into an otherwise chaotic bubble column behaviour. Though there is some published literature on the hydrodynamics of multi-stage bubble columns [14–28], these studies are largely restricted to superficial gas velocities below about 0.1 m/s. Also, there is no systematic study on the influence of increasing column diameter on the hydrodynamics of partitioned bubble columns.

Our objectives are to study the influence of partition plates on the liquid-phase backmixing characteristics in columns with varying diameters, operating at superficial gas velocities in the range 0.05–0.4 m/s. The

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results of our study can be expected to be useful for scale-up purposes.

2. Experimental

Backmixing studies were performed in three different cylindrical bubble columns with diameters of 0.10, 0.15 and 0.38 m. The columns were made up of several polyacrylate sections with varying lengths. The 0.1 m diameter column had a total height of 6 m, while the other two columns were 4 m in height. The columns were open at the top, hence the pressure corresponded with ambient conditions (101.3 kPa). Perforated plate spargers of identical design were used in all three columns to distribute the gas phase. The distributor plates were made up of brass with holes of 0.5 mm diameter distributed over the plate at a triangular pitch of 7 mm. Staging of the bubble columns was achieved by perforated brass plates, which were placed

Table 1
Experimental conditions and column configurations used during RTD experiments[a]

Operating conditions	Column diameter, D_T (m)		
	0.1	0.15	0.38
Location of probes (m)			
L_1	1.60	0.60	0.58
L_2	2.41	1.39	1.38
L_3	3.30	2.31	2.19
L_4	4.30	3.31	2.69
Plate location (m)			
H_{plate1}	2.04	2.08	1.00
H_{plate2}	4.08	–	–
Dispersion height (m)			
H_d	4.70	3.70	2.89

[a] Further experimental details are available on our web site: http://ct-cr4.chem.uva.nl/partition.

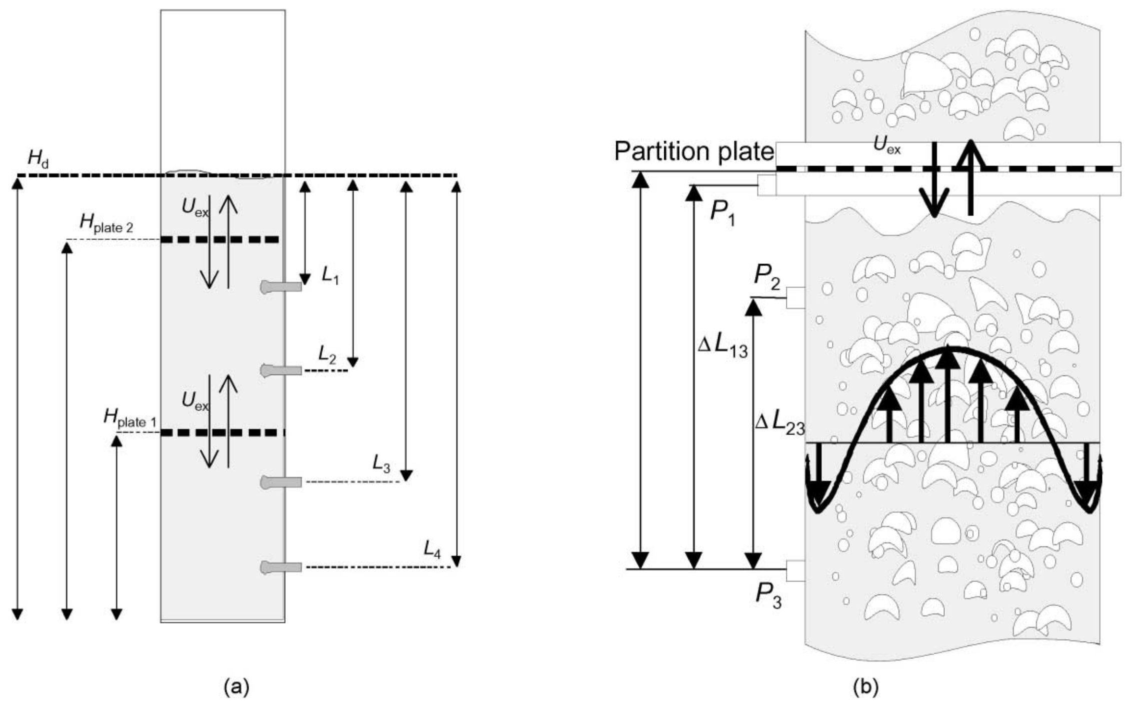

Fig. 1. (a) Schematic drawing of plate locations. The lengths are specified in Table 1. Refer to our web site for further experimental information: http://ct-cr4.chem.uva.nl/partition. (b) Experimental set-up to measure the gas cap size forming underneath the partition plates. U_{ex} represents the (absolute) velocity of liquid exchanging between compartments.

between sections of the bubble columns. The partition plate thickness was 1 mm, with 10 mm diameter holes. Since pressure drop over the plate needs to be maintained very low in commercial-scale applications, a relatively high open area of 18.6 and 30.7% was chosen for the experiments. Demineralised water was used as the liquid phase and air as the gas phase. All measurements were performed with the liquid in batch, therefore no liquid inflow or outflow was present. The air flow was controlled by means of Brooks flowmeters. Residence time distribution (RTD) of the liquid phase was determined using variable amounts of a saturated solution of NaCl (25 wt.%) as a tracer. The tracer was injected as a pulse just above the dispersion. The salt concentration was monitored with four Metrohm immersing-type conductivity cells, which were placed along the column height. The amount of tracer was chosen to get an optimal signal within the operating range of the conductivity cells (0–200 mV). In order to ensure a fast detection of the rapidly changing signal, the standard cells were slightly modified to give optimal response in a two-phase flow system. A slit of about 35 mm × 5 mm in the glass cover at the tip of the measuring device guaranteed fast access of the liquid phase and also prohibited an accumulation of gas bubbles inside the conductivity cell. The experimental conditions as well as the location of plates and conductivity cells are specified in Table 1 and shown schematically in Fig. 1(a). Additionally, experiments were carried out to measure the size of the gas layer forming underneath the partition plates; the set-up used for this purpose is shown in Fig. 1(b); the gas cap height was back-calculated from differential pressure measurements at two locations below the plate. Further details of the columns and partition plates along with measurement procedure are available on our website: http://ct-cr4.chem.uva.nl/partition.

3. Experimental results and discussion

At low gas velocities, $U_G < 0.02\,m/s$, the bubbles are uniformly dispersed along the column diameter and travel through the plate without much hindrance or interaction. An increase in the superficial gas velocity results in enhanced bubble coalescence just below the partition plate. Bubbles accumulate below the partition plate and are, subsequently, redistributed. For the 18.6% open area plate geometry used in the present study, bubbles start to coalesce below the plate at a superficial gas velocity of around $U_G = 0.1\,m/s$, thus forming a gas layer underneath the plate. A continuous liquid down-flow occurs from a stage to the one below indicating that liquid has to be lifted up to the stage above at the same time to satisfy the equations of continuity of mass. Churned-up by the fast rising large bubbles, a highly turbulent dispersion below the partition plate frequently reaches the partition plate carrying liquid to the upper section. The size of the gas cap steadily increases with superficial gas velocity and reaches values of up to 0.2 m for high superficial gas velocities, $U_G = 0.40\,m/s$ and small column diameters, $D_T = 0.10\,m$; see Fig. 2. The formation of a gas cap below the plate is not desirable, since it results in a decreased gas–liquid surface area and essentially wastes reactor space. It can be seen from Fig. 2 that the gas layer below the plate becomes, significantly, smaller when increasing the column diameter to $D_T = 0.38\,m$. This leads to the conclusion that the gas cap will not play a significant role in the scale-up of multi-stage bubble column reactors since it will diminish for large column diameters. This positive scale-up aspect of partitioned bubble columns has not been stressed in the literature.

We first measured the axial dispersion coefficients in the three columns without partition plates. The

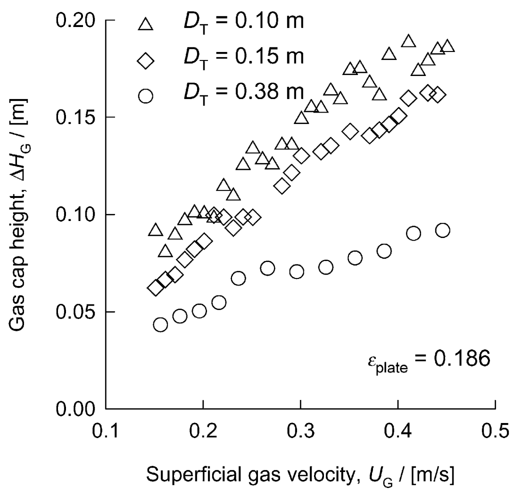

Fig. 2. Height of the gas cap forming below partition plates for three columns with diameters of 0.10, 0.15 and 0.38 m. Plates with an open area of 18.6% were used in this study.

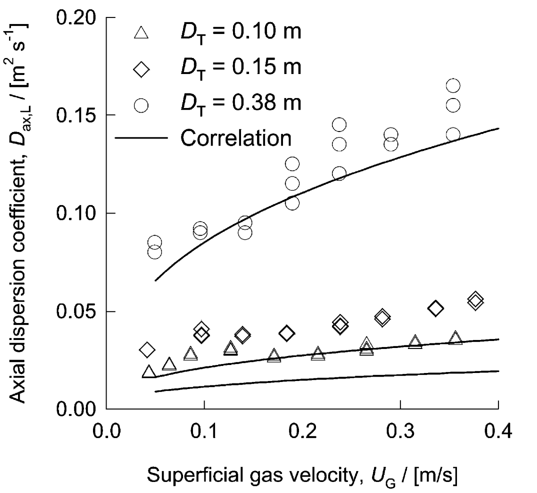

Fig. 3. Axial dispersion coefficients of the liquid phase measured in the empty bubble columns with diameters of 0.1, 0.15 and 0.38 m.

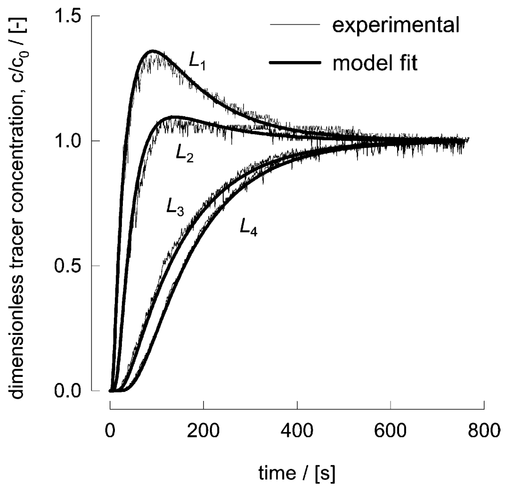

Fig. 4. Typical RTD curves obtained for 0.1 m diameter columns with two partition plates of 18.6% open area and $U_G = 0.255$ m/s. The smooth lines represent the fitted curves using the one-dimensional axial dispersion coefficient within a compartment along with liquid velocity exchange between compartments.

interpretation of the data is identical to that in our earlier publications [10,12] and the results are shown in Fig. 3. It can be seen that the values of the axial dispersion coefficient, $D_{ax,L}$, increase with increasing superficial gas velocity and with increasing column diameter. This is in reasonably good agreement with the vast amount of literature available in this area and the values agree reasonably well with the recently developed correlation [10,12].

For the interpretation of the backmixing in multi-stage operation, the axial dispersion within any stage is taken to be identical to that of an empty bubble column. The differential equation describing the variation of tracer concentration with time for any stage i is given by

$$\frac{\partial C_i}{\partial t} = D_{ax,L}\frac{\partial^2 C_i}{\partial z^2}, \quad z_i \le z \le z_{i+1} \tag{1}$$

with the initial condition of a pulse at $z = 0$ and $t = 0$. The boundary conditions at the top (stage 1) and bottom (stage N) of the column are of the closed type:

$$\frac{\partial C_1}{\partial z} = 0, \quad t > 0,\ z = 0,$$
$$\frac{\partial C_N}{\partial z} = 0, \quad t > 0,\ z = L \tag{2}$$

At the plate boundary, only liquid exchange flow is allowed. Therefore, the boundary conditions at the partition plates are

$$D_{ax,L}\frac{\partial C_i}{\partial z} = \frac{U_{ex}}{\varepsilon_L}(C_{i+1} - C_i), \quad t > 0,\ z = z_{i+1^-} \tag{3}$$

$$D_{ax,L}\frac{\partial C_{i+1}}{\partial z} = \frac{U_{ex}}{\varepsilon_L}(C_{i+1} - C_i),$$
$$t > 0,\ z = z_{i+1^+} \tag{4}$$

where U_{ex} is the superficial liquid exchange velocity through the perforated plate.

The RTD curves were therefore fitted to the model described above with only one adjustable parameter, the liquid exchange velocity, U_{ex}. Typical fits of the RTD curves measured at four locations (two in each stage, specified in Table 1) are shown in Fig. 4 for the 0.1 m diameter column. Similar excellent fits of the RTD curves were obtained for a whole range of gas velocities for all the three columns studied.

Fig. 5 shows the results of the liquid exchange velocity, U_{ex}, from fitted RTD curves as described above. For the 18.6% open area partition plate, it is seen that U_{ex} increases slightly with increasing superficial gas velocity U_G but there is no discernible trend with the column diameter D_T. For the 0.15 m diameter column measurements were also made with a partition plate

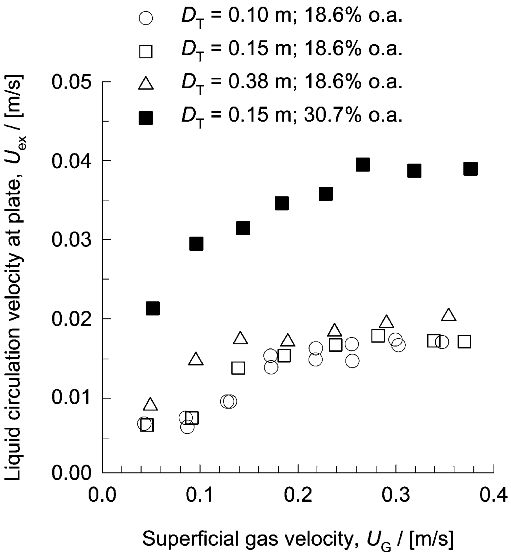

Fig. 5. Liquid exchange (superficial) velocities obtained from fitting the normalised tracer response curves with the dispersion with liquid exchange model.

with 30.7% open area. The exchange velocity is significantly higher in this case. The exchange velocity is, therefore, a strong function of the open area of the partition plate.

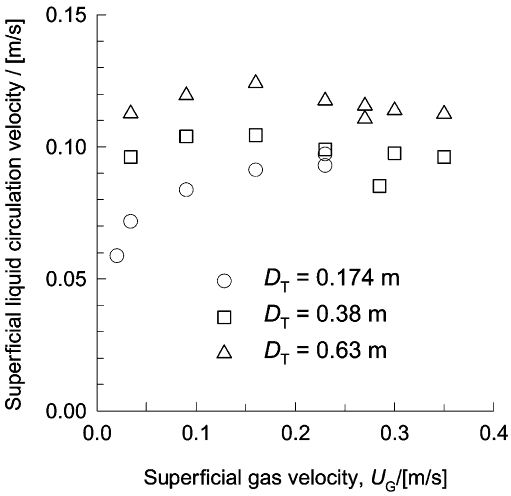

Fig. 6. Liquid circulation (superficial) velocities calculated from the CFD simulations of empty bubble columns reported in earlier work [10–12]. These circulation velocities were obtained by determining the upward and downward moving liquid flows, separately, by integrating the radial distribution of the liquid velocity.

For an empty bubble column, without partition plates, the liquid travels upwards in the central core and down the sides; see Fig. 1(b). From our earlier work [10–12] on the liquid velocity profiles, we can calculate the circulation velocity, which is the same in the upward and downward directions because there is no net flow. The values of these circulation velocities are shown in Fig. 6 for three column diameters. We note that the circulation velocities increase with increasing column diameter. Furthermore, the magnitude of the liquid circulations in an empty bubble column is about an order of magnitude higher than that obtained with the 18.6% open area partition plate (cf. Figs. 5 and 6). The strong influence of partition plates in depressing the liquid-phase backmixing is evident. Clearly, the suppression of the liquid-phase backmixing is crucially dependent on the free area of the partition plate.

4. Conclusions

Introduction of partition plates in a bubble column has the effect of severely restricting the liquid circulations between the compartments. The measured RTD curves were used to backcalculate the superficial liquid exchange velocity U_{ex} between the compartments. The values of U_{ex} were found to be practically independent of the column diameter. Increasing the free area of the partition plates from 18.6 to 30.7% increases the liquid exchange significantly. Our experimental results are helpful for scaling up multi-stage bubble column reactors.

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