Study of Axial Dispersion on Several Modern Structured and Random Packings

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Abstract. Axial dispersion is an undesirable phenomenon and it is not the subject of attention in the literature in the last years. Axial dispersion degrades efficiency of the separation equipment through reduction of the mass-transfer driving force, and in the limit, a column could behave like a single equilibrium stage. This work is focused on determination of axial dispersion in the form of Bodenstein number for liquid phase for five types of modern packings in a packed absorption column. Packings used in this work were random packings NeXRing0.7 and NeXRing1.2 and structured packings MellaPak350Y, 452Y and 500Y. The data obtained from dynamic experiments in the form of a response to a step change in tracer concentration, were compared to diffusion-type differential equation, which was solved with boundary conditions for a closed system. By measuring responses at two different packed bed heights and using convolution, the influence of end effects was eliminated.

Keywords Axial dispersion, Structured packing, Random packing

Introduction

A number of transport and hydraulic models / correlations have been developed for design of packed bed columns. Those models / correlations are mostly based on the assumption of an ideal plug flow. However, non-ideal hydrodynamics in the liquid phase can manifest itself significantly under conditions of normal distillation or absorption at low liquid velocities and high gas velocities. In the case of the gas phase, under normal conditions, the actual flow does not differ much from the ideal, which may not be the case at low gas velocities and high liquid velocities, which are commonly used in physical desorption of sparingly soluble gases (eg deoxygenation of water in beer production, etc.). The adverse effect of non-ideal phase flow is then even more significant in operations that are operated with a large number of transmission units. Neglecting the axial dispersion can also fundamentally distort the evaluated transport characteristics, which are crucial in the design of the device, and their application to cases other than those on which they were measured is then questionable.

Despite the fact that axial dispersion can have a significant effect on the design of packed mass exchangers, it has not received so much attention in the literature so far. Axial mixing has been studied thoroughly in first generation random packings (Raschig rings, Berl saddles). For example, studied were the effects of (i) mutual phase interaction (Dunn et al. (1977)), (ii) end effects (Sater et al. (1966)), (iii) packing length and its diameter (Hoogendoorn and Lips (1965)), (iv) wall flow (Farid and Guán (1979)), (v) viscosity and surface tension (von Stockar and Cevey (1984)). On the other hand, the data of the axial mixing for modern random (Intalox saddles) and structured (Mellapak) packings are rather limited (Macías-Salinas and Fair (1999) and (2000)) and the data available do not cover gas and liquid flow velocities used in a distillation column.

Experimental part

All experiments were performed in a pilot-plant absorption column with an inner diameter of 290 mm under atmospheric pressure and 20 °C. Table 1 then summarizes used liquid and gas phase velocities. As a tracer, the NaCl was used and its concentrations in the liquid phase was kept below 1 g/l.

The experimental transient characteristic F_{exp}^{short} was measured on a column with short packed bed (hereinafter referred to as short column). Packed bed consisted of a column head and sump and two 10 cm pieces of structured packing MellaPak250Y rotated by 90°, which served to improve the distribution of the liquid phase throughout column cross section. When measuring the transient characteristic F_{exp}^{long} (hereinafter referred to as long column) a column of the same arrangement as in the measurement of F_{exp}^{short} was used but the packed bed was extended by a section of the studied packing. Distances between the liquid phase distributor and the beginning of the packing and between the bottom of the column and the end of the packing were maintained the same in both cases. For more details, see Valenz at al. (2010).

Table 1: Used liquid load (*B*) and gas velocity (u_G), diameter of nozzles in liquid distributor, liquid velocities from nozzles

B [m/h]	u_G [m/s]	Nozzle diam. [mm]	*v* [m/s]
2.5	0.0	2	0.9
5.0		2	1.8
10.0	1.0	3	1.6
20.0		4	1.8
40.0	2.0	7	1.2

Theoretical part

Axial dispersion of a tracer that flows along column mass transfer exchangers has been described in this work, similarly as it is in the works of other authors, by Fick's diffusion model. In this model, the molecular diffusion coefficient is replaced by an effective dispersion coefficient D_e. Then the tracer movement in the column is described through the material balance of the tracer over a differential element dz of the packed bed:

$$\frac{\partial c}{\partial t} = D_e \frac{\partial^2 c}{\partial z^2} - u_i \frac{\partial c}{\partial z} \qquad (1)$$

Axial dispersion coefficients are usually given in the form of dimensionless Péclet (based on packing characteristic dimension) or Bodenstein number (based on packed bed height) see equations (2) and (3). These numbers come from the dimensionless analysis of equation (1) and are inversely proportional to the effective axial dispersion coefficient D_e. Thus, the higher is the value of the dimensionless number the lower is the axial dispersion.

$$Pe = \frac{u d_p}{D_e} \qquad (2)$$

$$Bo = \frac{uL}{D_e} \qquad (3)$$

One initial and two boundary conditions are needed to solve equation (1). These vary depending on the tracer being introduced into the system. In this work, a step change was chosen for which the normalized tracer concentration is zero at all points inside the column before injection begins, see initial condition (4). The boundary condition (5) describes the step change in the tracer concentration after it has entered the packing. A boundary condition (6) is then used at the column outlet, which states that the tracer concentration at the column outlet is a continuous function.

$$c(z, t \leq 0) = 0 \qquad (4)$$

$$u_i \cdot c(0^-, t) = u_i \cdot c(0^+, t) - D_e \frac{\partial c(0^+, t)}{\partial z} \qquad (5)$$

$$\frac{dc(L, t)}{dz} = 0 \qquad (6)$$

Before the solution itself, equation (1) was converted to a dimensionless form to simplify the problem. Dimensionless spatial coordinates are introduced here $Z = \frac{z}{L}$, where L is packed bed height and dimensionless time $T = \frac{t}{t_m}$, where t_m is mean residence time and concentration $F = \frac{c}{c_0}$. For the outlet of the column (Z = 1) can be found the analytical solution (7) (Valenz et al. (2010)):

$$F_{vyp}(1, T) = 1 + 4\alpha e^{\alpha} \sum_{j=1}^{\infty} k \frac{{B_j}^2}{\left(\alpha^2 + {B_j}^2\right)\left({B_j}^2 + \alpha^2 + 2\alpha\right)} \exp\left\{-\frac{{B_j}^2 + \alpha^2}{2\alpha} T\right\} \qquad (7)$$

Where Bj are the roots of the equations:

$$B_j \, cotg \, \frac{B_j}{2} + \alpha = 0, \quad k = +1 \qquad (8)$$

$$-B_j \, tg \, \frac{B_j}{2} - \alpha = 0, \quad k = -1 \qquad (9)$$

$$\alpha = \frac{Bo}{2} \qquad (10)$$

The solution of equation (7) provides a model tracer concentration response only on the packing. Convolution together with experimental response on the short column should provide the response corresponding the experimental one on the long column. The parameters, which influence the fit, are effective dispersion coefficient and mean residence time. The simplex method has been used to search for the optimal pair of parameters [t_m, Bo]. Minimization has been performed until the differences in the values of the parameters in the two following steps were lower than 10-5. This two-response method eliminates the effects of the probe dynamics, the imperfection of the tracer step change, and the ends effects. For more details, see Valenz at al. (2010).

Results and discussion

Figure 1 plots the experimental values of the Bodenstein number in the liquid phase (Bo_L) for Mellapak 350Y (M350Y) including 95% confidence intervals. Bo_L values are shown in dependence on the velocities of both phases and in comparison with the values for Mellapak 250Y[1] (M250Y). Bo_L values range from 12.6 to 52.2 and are not affected by the gas velocity up to u_G = 1 m/s within the scatter of the experimental data. For the gas velocity of u_G = 2 m/s, the values of the Bodenstein number are on average 20% higher than without the gas flow. The average value of the exponent at the power dependence of the Bodenstein number on the liquid velocity is equal to 0.51. Axial dispersion is at low liquid velocities comparable to dispersion at M250Y, at high velocities the values of Bodenstein number for M350Y are about 30% higher.

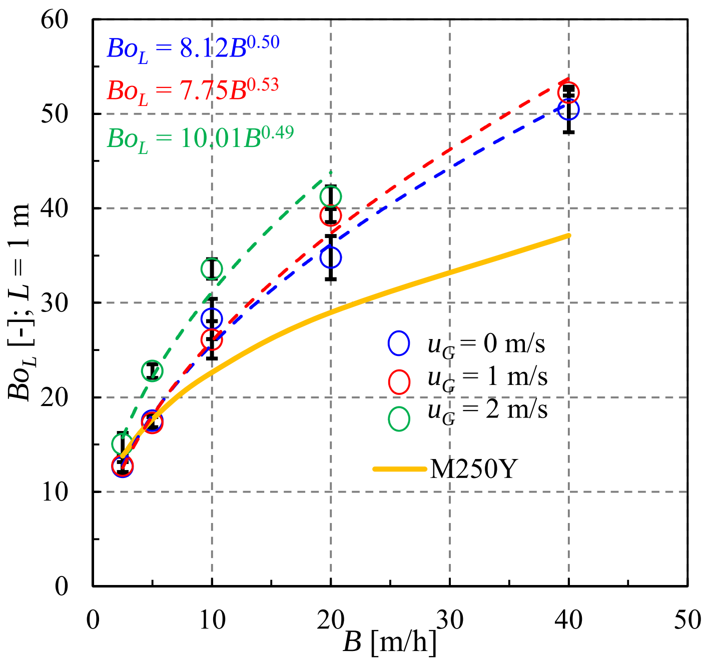

Fig. 1 Values of Bo_L in dependence on phases velocities for M350Y packing

Figure 2 plots the experimental values of the Bo_L for Mellapak 452Y (M452Y) including 95% confidence intervals. Bo_L values are shown in dependence on the velocities of both phases and in comparison with the values for M250Y[1] and M350Y. The values of the Bo_L, which range from 18.7 to 61.3, increase with increasing liquid flow and up to u_G = 1 m/s are independent on the gas velocity. For a gas velocity of u_G = 2 m/s, these values are on average 30% higher than without a gas flow. The average value of the exponent at the power dependence of Bo_L on the liquid velocity is equal to 0.42. Compared to the M250Y packing, the values of the Bodenstein number for M452Y are about 56% higher. Despite the fact that M452Y has the same characteristics as M350Y, almost 30% lower axial dispersion was measured on this packing. Whether this fact is caused by an adjustment in the case of M452Y, which consists in straightening the channel at the beginning and end of each packing element, it is necessary to further verify on other packing from the same series.

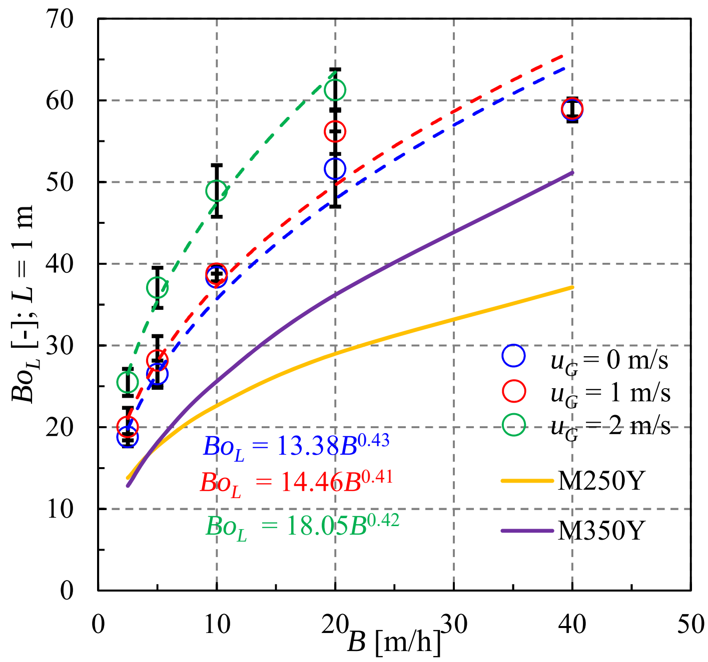

Fig. 2 Values of Bo_L in dependence on phases velocities for M452Y packing

Figure 3 plots the experimental values of the Bo_L for Mellapak 500Y (M500Y) including 95% confidence intervals. Bo_L values are shown in dependence on the velocities of both phases and in comparison with the values for M250Y[1]. The values of the Bo_L in the case of the M500Y packing range from 12.5 to 30.9 and increase with the increasing liquid velocity. The exponent of the power dependence of the Bodenstein number on the liquid velocity has an average value of 0.34, which is the lowest one of all structured packings studied in this work. The axial dispersion values are independent of the gas velocity over the entire range of conditions used. Compared to the M250Y, the axial dispersion for the M500Y is about 10% higher.

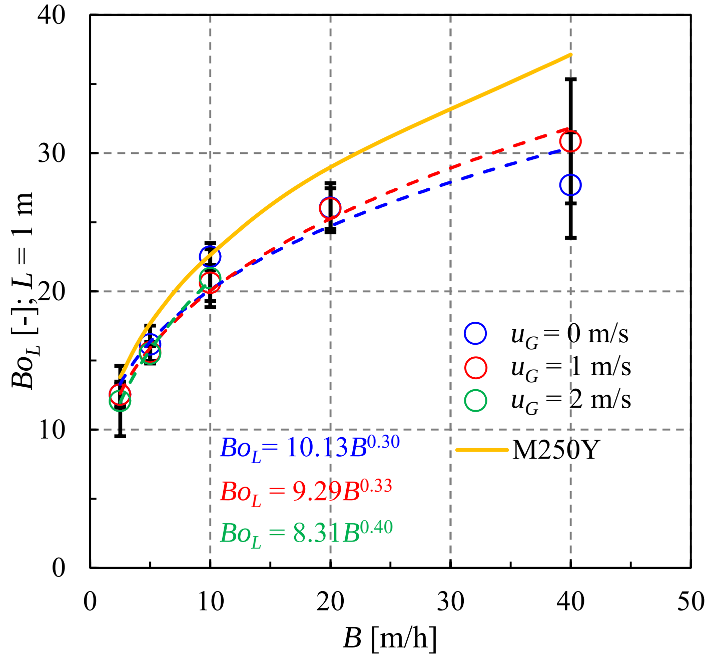

Fig. 3 Values of Bo_L in dependence on phases velocities for M500Y packing

Figure 4 plots the experimental values of the Bo_L for NeXRing 0.7 (NXR0.7) including 95% confidence intervals. Bo_L values are shown in dependence on the velocities of both phases and in comparison with the values for M250Y[1], Pall rings 25mm[1] and Intalox saddles 25 mm[1]. The values of the Bo_L range from 7.2 to 19.0 and, as in the previous packings, increase with the increasing liquid flow. The axial dispersion for NXR0.7 is about twice larger compared to M250Y. In the case of random packings, NXR0.7 has an axial dispersion comparable to that of the Pall rings 25 at high liquid velocities, and a dispersion about 60% lower at lower ones. Intalox saddles 25 have an axial dispersion almost 10 times higher than NXR0.7 at liquid velocity B = 2.5 m/h, this difference decreases with increasing velocity.

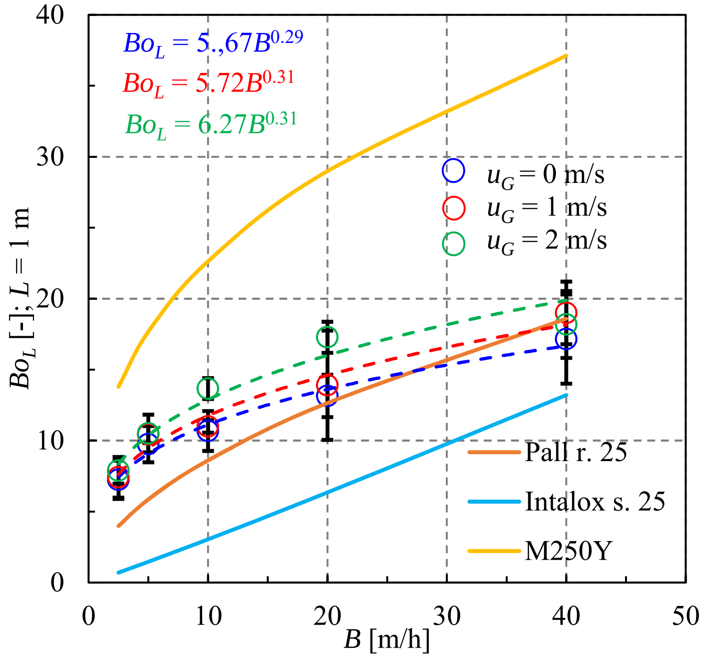

Fig. 4 Values of Bo_L in dependence on phases velocities for NXR0.7 packing

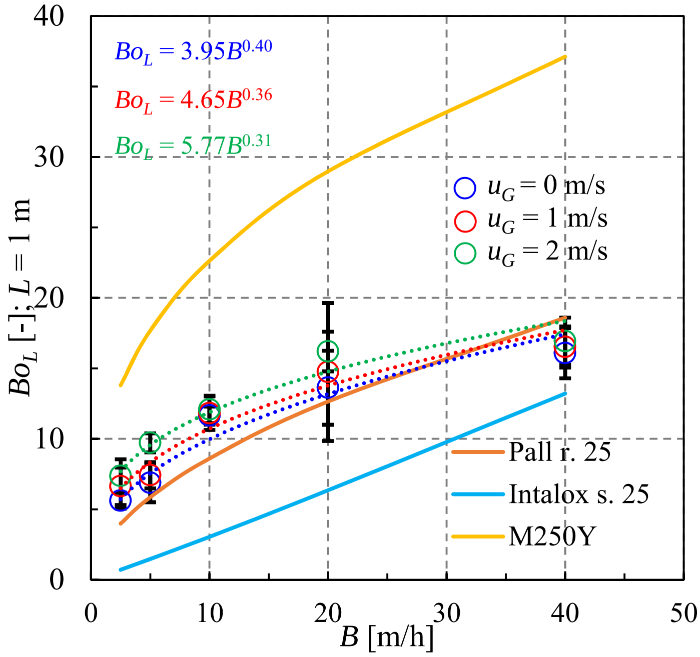

Fig. 5 Values of Bo_L in dependence on phases velocities for NXR1.2 packing

Figure 5 plots the experimental values of the Bo_L for NeXRing 1.2 (NXR1.2) including 95% confidence intervals. Bo_L values are shown in dependence on the velocity of both phases and in comparison with the values for M250Y[1], Pall rings 25mm[1] and Intalox saddles 25 mm[1]. The Bo_L values range from 5.6 to 16.9 and, as in the previous packings, show an increasing trend with increasing liquid velocity. The exponent of the power dependence of the Bodenstein number on the liquid velocity has an average value of 0.36. At higher liquid velocities, the axial dispersion for NXR1.2 is comparable to Pall rings; at lower velocities, the Bo_L values for NXR1.2 are about 30% higher. Intalox saddles have Bo_L values up to 8 times higher than NXR1.2 for low liquid velocities, but with increasing velocity this difference decreases and for B = 40 m/h Bo_L differs by only 20%. M250Y then shows about 55% lower axial dispersion than NXR1.2.

Conclusion

In total five types of modern packings have been studied, which have not yet been studied in terms of axial dispersion. These are three structured packings MellaPak350Y, MellaPak452Y and MellaPak500Y, as well as two random packings NeXRing0.7 and NeXRing1.2. It was found that the values of the Bodenstein number are comparable for structured packings M250Y, M350Y and M500Y at low liquid velocities. At high velocities, the values of the Bodenstein number are the highest for M350Y and the lowest for M500Y. Furthermore, it was found that despite the fact that M350Y and M452Y are practically identical in terms of main parameters and differ only in different angles of channel inclination in the first and last 3 cm of packing element, the values of Bodenstein number for M452Y in the whole range of liquid and gas velocities are higher. Whether the channel alignment of the M452Y has an effect on this remains a question, and these findings need to be further verified by measuring the axial dispersion on other packings from the same series.

For MellaPak350Y and 452Y, an increase in the Bodenstein number values was further observed with increasing gas velocity. We believe that this is influenced by the wall flow, the effect of which decreases with increasing gas velocity and almost disappears at u_G = 2 m/s, which could be observed visually during the experiments.

The values of the Bodenstein number for the studied random packings are lower than for the above-mentioned structured packings. On the other hand, in comparison with Pall rings 25 mm or Intalox saddles 25 mm, the values of Bodenstein number for NXR0.7 and NXR1.2 are up to twice as high. Therefore, it seems that the packings of NeXRing series suppresses the effect of undesired axial dispersion, which is quite significant for other types of random packings.

Acknowledgements

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