On the Phases’ Distribution in Packed Columns

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Abstract. Packed columns are typical apparatuses for industrial separation processes which are important in fuel and energy production and reduction of harmful emissions in the atmosphere. The efficiency of the processes in them is strongly dependent on the regular distribution of phases. The liquid and gas maldistribution has been the subject of long intensive investigations. The formation of a liquid wall flow has been found to be one of the main factors for the large-scale radial irregularity of liquid and gas distribution. The prediction and control of this phenomenon is still unsatisfactory. Our work suggests a new approach for evaluation of the wall flow in countercurrent absorption with random packings. It uses simple mathematical apparatus and is based on experimental data of the wall flow along the column height. It allows gaining knowledge about the liquid flow and evaluating the wall flow volume as a criterion of efficiency for comparison of packings. The model is demonstrated by a case study with data for metal Pall rings.

1. Introduction

The efficiency of separation processes like absorption and distillation in column apparatuses is dependent on the distribution of the gas and liquid in the packed bed.

Investigations on liquid maldistribution in random packings have been conducted at varying experimental and operating parameters – column diameter, initial liquid and gas load, type of packing, packing height, liquid distributor, surface tensions etc. The formation of a liquid wall flow is the main factor for radial irregularity of the phases. Extensive information is available on the factors affecting the development of the liquid wall flow along the bed depth, in gas-liquid counter current flow [1-3]. It can be concluded also that each packing (type/size, random/structured) forms individual wall flow profiles along the bed depth even with perfect initial distribution on the top [1]. The experiments with random packings of the same type and different nominal size have shown that the wall flow increases with the nominal size. The design of the liquid distributor, i.e. the initial flow pattern, is another important factor for the liquid distribution in random packings [3]. Hanusch et al. [4] investigated these effects in modern packings at industrial scale and regimes. They observed that the wall flow increases with the gas load (more sharply below the loading point). Irrespective of the vast research, the problem of precise prediction and control of the formation of the wall flow is still unsolved.

The modeling and simulation of the mass transfer processes in column apparatus is difficult due to the unknown velocity distribution in the gas and liquid phases and the unknown interface boundary. These problems were surmounted in the monographs [5-7] by convective-diffusion models, where the
unknown surface velocities of processes are replaced by equivalent volume velocities, and average-concentration models, where the velocities and the concentrations of the phases are replaced by velocities and concentrations averaged in the column cross-section. The theoretical analysis in these monographs demonstrated that the mass transfer rate in the phases depends on the radial irregularity of the axial velocity component and decreases with the irregularity increase.

A widely spread approach in literature for modeling the wall flow is based on solving a diffusion type differential equation for the liquid distribution by introducing a coefficient of radial liquid spreading $D_r [m]$ and various boundary conditions at the wall [1, 2, 8-11].

The present work suggests a new approach of evaluation of the wall flow. It is based on a simple mathematical function describing the thickness of the wall flow along the packing depth. By simple mathematical transformations it gives the possibility to evaluate the liquid volume in the layer covering the wall, which bypasses the mass transfer processes, and is therefore responsible for the reduction of the mass transfer efficiency.

2. Effect of the random packing in packed columns

The modeling and simulation of the absorption processes in countercurrent column apparatus uses mass balances in the gas and liquid phases. For this purpose, the volume fractions of the phases (the volumes of phases per unit volume of the column) are used:

$$\varepsilon_j, \quad j = 0,1,2, \quad \varepsilon_0 + \varepsilon_1 + \varepsilon_2 = 1,$$

where the indices $j = 0,1,2$ correspond to solid, gas and liquid phase.

In case of absorption modeling in columns with random packings, an additional problem arises from the existence of a liquid flow on the column wall that does not participate in the absorption process. The liquid phase is thus divided into two parts:

$$\varepsilon_0 = \varepsilon_{01} + \varepsilon_{02},$$

where $\varepsilon_{02}$ is the volume fraction of the liquid flowing down the wall of the column.

In absorption in random packings, the liquid flows along the surface of the randomly packed elements and, when reaching the column wall, the most of it flows down the wall surface and cannot return to the volume of the column due to the small contact surface between the wall and the packing elements. The thickness of the liquid layer on the wall increases and conditions are created for liquid backflow from the layer to the packing. The two effects are further equalized and in this way the liquid layer reaches a maximum thickness, constant to the bottom of the packed bed and the relative liquid superficial velocity of the wall flow reaches equilibrium value [1, 2]. The latter is expressed in [1], based on a diffusion model, as a function of the ratio of the column diameter to the packing element diameter.

The amount of liquid entering the liquid layer results in a decrease in the amount of liquid in the column bulk, i.e. in radial irregularity of the axial component of the liquid velocity, as well as in the reduction of the mass transfer rate in the liquid phase. In addition, this layer is not involved in the absorption process.

The effect of the liquid flow down the column wall in random packings is solely the result of the geometric shape of the packing elements, which determines the packing surface area per unit volume of the column. In this way, the geometric shape of the packing elements strongly affects the absorption rate of poorly soluble gases, which reaches a maximum value at a maximum packing surface area and a minimum thickness of the wall flow liquid layer.

But the approaches for comparison of the packings are not universal, since the packing efficiency depends not only on the packing material and geometry, but also on variables connected with the specific separation system [12]. It was reported by Hanley [13] that liquid maldistribution in the packed bed affects the efficiency of separation processes through an increase of the HETP (the height of an equivalent theoretical plate) in relation to no maldistribution, a decrease in the specific pressure
drop relative to the same packing height with regular distribution, and an increase in the total pressure drop for the required separation. As a characteristic maldistribution parameter he introduced the ratio of more wetted column area to less-wetted column area defined by $\zeta = r_d^2 r_0^{-2}$, where $r_d$ [m] is the radius dividing the two areas and $r_0$ [m] is the column radius.

The experimental evidence in literature [1, 2] for the growth of the wall flow to an equilibrium state shows that the thickness of the wall flow liquid layer in columns with random packings increases smoothly from zero to a maximum equilibrium value $\delta_{\text{max}}$ [m]. There are cases [1], depending on the initial distribution, when the initial wall flow thickness can be greater than 0, but they are not considered here. It is assumed that the layer thickness can be represented by an asymptotic function $\delta(z)$ [m], which passes through point (0,0) and has a horizontal asymptote:

$$\delta(z) = \frac{z}{a + bz}, \quad \delta(0) = 0, \quad \delta(\infty) = \frac{1}{b} = \delta_{\text{max}}.$$  (3)

where $z$ [m] is the axial coordinate and the parameters $(a, b)$ are determined by experimental data.

The theoretical analysis presented shows that the packing efficiency is related to the wall flow and therefore to the parameters $(a, b)$, which can be obtained from the flow rate of the wall flow. The importance of the measurement accuracy should be emphasized. The measured amount of liquid on the wall should not include any liquid from the volume of the column. Methods and experimental data have been proposed for this purpose in [1-3].

The integration of function (3) along $z$ from 0 to $l$, where $l$ [m] is the packing layer height in the column, allows determining the value $V$ [m$^3$m$^{-1}$], which is the wall flow volume per unite periphery ($2\pi r_0$) and is related to the liquid, not involved in the absorption process, and therefore to packing efficiency:

$$V = \int_0^l \frac{z}{a + bz} dz = \frac{a b}{b^2} \left( \frac{b}{a} l - \ln \frac{a + bl}{a} \right).$$  (4)

The reciprocal of the wall film volume $E = V^{-1}$ [m$^3$] can be used as a characteristic maldistribution parameter for comparison of packings at a given separation system and with the same initial liquid distribution.

The determination of the packing efficiency is connected with the equilibrium length of the liquid layer on the wall $l_0$, when the layer thickness reaches 95% of its maximal value $\delta_{\text{max}} = b^{-1}$.

After obtaining $(a, b)$ by Eq. (4) and $\delta(z)$ by Eq. (3), it is possible to calculate $l_0$ from the equations:

$$0.95\delta_{\text{max}} = \frac{0.95}{b} = \frac{l_0}{a + bl_0},$$  (5)

i.e.

$$l_0 = \frac{19a}{b}.$$  (6)

The equilibrium wall flow $V_0$ at $l = l_0$ is obtained directly from Eq. (4):

$$V_0 = 16.0043 \frac{a}{b^2}.$$  (6a)

The maldistribution parameter $E$ is obtained as:

$$E = V_0^{-1}.$$  (7)

The presence of the wall flow in random packings implies that the absorption process takes place in a packed column with a variable radius $R$:
\[ R = r_0 - \delta(z). \] (8)

The presented analysis shows that the value \( E \) can be obtained after determining the width of the wall flow \( \delta(z) \), i.e. the parameters \((a,b)\) in Eq.(3).

3. The wall flow width

In order to find the width of the wall flow \( \delta(z) \), it is assumed that the average velocities of the liquid in the wall flow and in the bulk are:

\[
\frac{v_0}{2}, \quad \frac{v^* + v_0}{2}.
\]

where \( v_0 \) [ms\(^{-1}\)] is the surface velocity of the wall liquid layer, \( v^* = \frac{Q_L}{\varepsilon z \pi r_0} \) [ms\(^{-1}\)] is the mean liquid velocity in the cross-section area occupied by the liquid, \( \varepsilon \) is the liquid volume (area) fraction and \( Q_L \) [m\(^3\)s\(^{-1}\)] is the total liquid flow rate.

The experimental values of \( Q(z)_i, i = 1, \ldots, n \) give the possibility to calculate the flow rate of the wall flow per unit periphery (2\(\pi r_0\))

\[
Q(z)_i = \frac{Q(z)_i}{2\pi r_0}, \quad i = 1, \ldots, n.
\] (9)

The flow rate of the wall flow \( Q(z) \) can be expressed by the average velocities of the liquid on the wall and in the bulk as a subtraction of the wall flow rate from the total liquid flow rate in the column:

\[
Q(z) = \frac{\delta(z) v_0(z)}{2} = \varepsilon z r_0 v^* - \varepsilon z (r_0 - \delta(z)) \frac{v^* + v_0(z)}{2}.
\] (10)

From Eq.(10) a quadratic equation is obtained for \( \delta(z) \):

\[
[\delta(z)]^2 + r_0 \delta(z) - \frac{2 r_0 Q(z)}{v^* \varepsilon z} = 0.
\] (11)

where

\[
r_0^* = \frac{v^* \varepsilon z r_0 + 2 Q(z) \varepsilon z - 2 Q(z)}{v^* \varepsilon z}.
\] (11a)

The solution is

\[
\delta(z) = \frac{1}{2} \left\{ -r_0^* + \left( r_0^* + \frac{8 r_0 Q(z)}{v^* \varepsilon z} \right)^{1/2} \right\}.
\] (12)

The obtained experimental values of \( \delta(z) \) from Eq. (12) allow determining the parameters \((a,b)\) in Eq. (3) by minimizing the function of the least square differences

\[
F(a,b) = \sum_{j=1}^{n} \left( \delta(z_j) - \frac{z_j}{a + b z_j} \right)^2.
\] (13)

The calculated values of the parameters \((a,b)\) are introduced in Eq. (6) to calculate the parameter characterizing the packing maldistribution \( E \), Eq. (7).
4. Case study

The parameters of the described model Eq. (3) are determined from the experiments [3] as follows:

Conditions:

System water-air, uniform initial liquid distribution, liquid load \( L_0 = 6.66 \times 10^{-3} \text{m}^3\text{m}^{-2}\text{s}^{-1} \), gas load \( G = 0.625 \text{m}^3\text{m}^{-2}\text{s}^{-1} \), metal Pall rings 25, column radius \( r_0 = 0.3 \text{m} \). It is pointed out in [3] that the wall flow has not reached the fully developed state at the maximal packing height of 3.5 m, which can be seen in Fig. 1. The ordinate in the figure gives the relative wall flow, i.e. the ratio of the wall flow superficial velocity \( L_w \) \([\text{m}^3\text{m}^{-2}\text{s}^{-1}]\) over the collecting annulus area to the total liquid superficial velocity \( L_0 \) \([\text{m}^3\text{m}^{-2}\text{s}^{-1}]\) over the column cross-section area.

Details of the calculations and numerical values are presented in the Appendix.

The obtained results for the wall liquid layer thickness at different packing heights \( z \) are processed by minimizing the function of the least square differences Eq. (13). The constants in the model function Eq. (3) are determined with a satisfactory coefficient of determination \( R^2 = 0.89 \) and the function of the wall layer thickness can be expressed as follows:

\[
\delta(z) = \frac{z}{206.6 + 257.8z}
\]

This function allows calculating the equilibrium thickness of the wall flow layer, equal to about 4 mm (see Appendix), as well as the relative wall flow along the packing height, Fig. 1. The figure shows the good agreement of the model wall flow with experimental data.

![Figure 1. Wall flow superficial velocity: comparison of model with experimental data [3], water-air \( L_0 = 6.66 \times 10^{-3} \text{m}^3\text{m}^{-2}\text{s}^{-1} \), \( G = 0.625 \text{m}^3\text{m}^{-2}\text{s}^{-1} \), metal Pall rings 25, \( r_0 = 0.3 \text{m} \).](image)

Conclusions

The theoretical analysis of absorption in countercurrent flow columns with random packings shows that the main problem in modeling the hydrodynamics and mass transfer is the appearance of two liquid phases (in the bulk and on the surface of the column wall). This necessitates accurate experimental measurement of the flow rate of the liquid layer flowing down the column wall using suitable and accurate experimental methods. The experimental data allow determining part of the column volume, not involved in the absorption process, which can be used for comparative evaluation of the packings. Its reciprocal value can serve as a characteristic maldistribution parameter for comparison of packings at a given separation system and with the same initial liquid distribution.

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Appendix

Calculations for the case study, based on data from [3]:

Experimental conditions: system water-air, uniform initial liquid distribution, liquid load \( L_0 = 6.66 \text{e-3 m}^3\text{m}^{-2}\text{s}^{-1} \), gas load \( G = 0.625 \text{m}^3\text{m}^{-2}\text{s}^{-1} \), stainless steel Pall rings 25, column radius \( r_0 = 0.3 \text{ m} \).

For point 1 (all variables have index 1) in Figure 1 at packing height \( z_1 = 0.9 \) the relative superficial liquid velocity of the wall flow is \( L_{W1}/L_0 = 3.2 \) and we calculate:

\[
L_{W1} = 0.0213 \text{ ms}^{-1} \\
A_w = \pi (r_1^2 - r^2) = 0.008414 \text{ m}^2 \\
Q^*(z_1) = \frac{L_{W1}}{A_w} = 0.0001793 \text{ m}^3\text{s}^{-1},
\]

where \( r \) is the internal radius of the wall flow collecting annulus.

For calculating the area of the wall flow collecting annulus \( A_w \), the annulus width is \( (r_0 - r) = 4.5 \text{ mm} \) [3].

For \( i = 1 \), \( Q(z_1) = 9.518 \text{ e-5 m}^3\text{m}^{-2}\text{s}^{-1} \) (Eq. 9)

The liquid volume fraction \( \varepsilon_2 = 0.062 \) is taken from experimental data for metal Pall rings 25 [14] for \( L_0 = 6.66 \text{ e-3 m}^3\text{m}^{-2}\text{s}^{-1} \) and the mean liquid velocity in the area occupied by the liquid is calculated:

\[
v_\theta = L_0 \varepsilon_2 = 0.1074 \text{ ms}^{-1}.
\]

Introducing the values \( Q, \varepsilon_2 \) and \( L_0 \) in Eq. (11a) we calculate

\[
r_0' = 0.2732, \text{ and then } \\
\delta(z_1) = 1.93e-3 \text{ m} \text{ (Eq. (12)).}
\]

The same steps are repeated with all data points in Figure 1 to calculate the wall liquid layer thickness \( \delta(z_i) \) at different packing heights \( z_2 = 1.8 \text{ m} \) and \( z_3 = 3 \text{ m} \).

The results for \( \delta(z_i) \) are processed by nonlinear regression, minimizing the function of the least square differences, Eq.(13). The constants in the model function Eq.(3) are determined with a coefficient of determination \( R^2 = 0.89 \) as \( a = 206.6, b = 257.8 \). This allows calculating the following results:

\[
\delta_{\text{max}} = b^{-1} = 0.0039 \text{ m} \\
V_0(0.95\delta_{\text{max}}) = 0.0497 \text{ m}^2 \text{ (Eq. 6a)} \\
l_n = 15.22 \text{ m} \text{ (Eq. 6)} \\
E = 20.12 \text{ m}^2 \text{ (Eq. 7)}
\]

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