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Research Article

Liquid distribution in a semi-industrial packed column - experimental and theory

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Abstract

The scientific interest in the efficiency of packed bed columns is part of the world-wide pursuit of sustainability of processes. The maldistribution of the phases in the apparatus reduces the efficiency and makes difficult the prediction of process performance and scaling up. In the present work the operation of liquid distribution devices and high performance packings are investigated addressing the reasons for hydrodynamic non-uniformity of the liquid phase, including the formation and development of wall flow. Data are obtained from semi-industrial size experimental studies and mathematical modelling of the liquid flow through a layer of random Raschig Super-Ring packing. The effect of measures for ensuring uniform initial liquid distribution in the column apparatus is evaluated and the parameters in the mathematical model are identified.

Practical applications: Packed columns are typical apparatuses for absorption, desorption, rectification and direct heat transfer with applications in power industry, biofuel technologies, and food production.

Keywords: packed bed column, liquid distribution, Raschig Super-Ring, random packing, mathematical modelling.

Abbreviations:

RSRM – Raschig Super-Ring

LCD – liquid collecting device

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Introduction

Packed columns are common for separation processes in food technologies. In continuous distillation they are widely employed along with tray columns, the packed bed having lower pressure drop. The operation of a packed column is strongly affected by the uniform distribution of the phases. The maldistribution of the liquid phase can reduce the mass transfer efficiency up to 50% (Stichlmair and Stemmer 1987).The liquid distribution in the column strongly depends on the initial liquid uniformity. Correct prediction of concentration distribution is possible only based on detailed knowledge of the flow pattern. Adequate modeling of mass transfer needs taking into account the effects of flow maldistribution. On the base of a physical experiment, a mathematical model is developed with the purpose to predict the liquid superficial velocity distribution and the wall flow in a packing bed of modern high performance metal packings Raschig Super-Ring (RSRM). This is a random packing, which is currently widely applied in new plants and in revamp from trays or structured packing, due to its advantages connected with turbulence generating geometry and large interfacial area at low pressure drop. The present study aims at obtaining detailed experimental data on liquid distribution in metal RSRM 1.5" packing in a semi-industrial size column. The target is the liquid spreading and wall flow. Special attention is paid to the liquid distributor to ensure the validity of the model assumption of uniform initial velocity profile and to study the effect of initial irregularity on the distribution in the packing bed.

Materials and Methods

Experimental. The materials and methods are explained in detail in Dzhonova et al. (2014). The main unit of the experimental installation is a steel column of a 470 mm diameter. The measurements are performed by means of the liquid collecting method with an annular liquid collector under the packing layer in one phase flow of tap water at room temperature fed at the top of the column at superficial velocities from L_0=3x10^{-3} to 12x10^{-3} m^{3}m^{-2}s^{-1} (liquid flow rate Q_0 = 1.87 – 7.49 m^{3}h^{-1}). The modeling approach based on the study of Staněk and Kolář (1967), needs data from two types of initial distribution, uniform over the column cross-section, and peripheral only on the column wall, which are provided by two types of liquid distributors. The uniform liquid distributor is a plate with evenly distributed drip points in the vertices of equilateral triangles. In order to eliminate the vortices from water feeding into the distributor's section, it is filled with a 250 mm redistribution layer of RSRM 1.5" on a supporting grid at a small distance (38 mm) over the distributor plate. The measurements of the flow rates of the individual drip points showed that this packing layer improves the deviations from the mean, which are 12-13% without redistribution packing, to 1% with redistribution packing. To prevent liquid flowing from the distributor directly on the column wall, the distance from the wall to the nearest peripheral points should not exceed half the triangle side. Therefore, at the column wall the triangular pattern is not strictly followed. Differences in the density of the peripheral points affect the initial distribution and the formation of the wall flow. Two cases are examined, case 1 with 61 points and case 2 with 85 points (24 more peripheral points), Fig. 1.

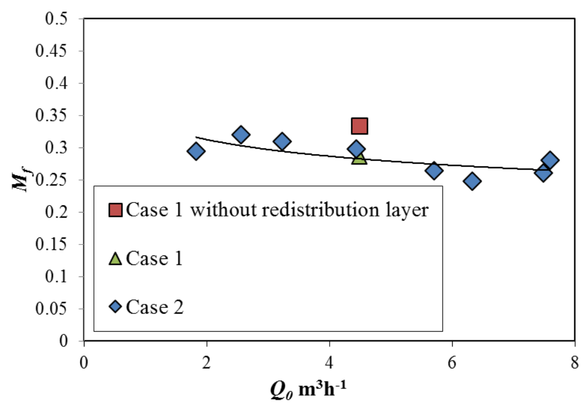


Figure 1. Comparison of initial distribution case 1 and 2

Measurements of liquid distribution are carried out at packing heights of H=0.15 m and H=0.6 m. The first value is chosen as a minimal bed height which is necessary to transform the discrete rivulets from the drip points into uniform flow distribution over the bed cross section. This bed height is used for testing the initial uniformity evaluated by the maldistribution factor M_f, presented in Fig. 1 for case 1 and 2. Here the liquid maldistribution factor M_f is defined as follows:

$$M_f = \sqrt{\frac{1}{F_0}\sum_{i=1}^{n} F_i \left(\frac{\frac{Q_i}{Q_0} - W_0}{W_0}\right)^2}$$

$$W_o = \sum_{i=1}^{n} \frac{F_i}{F_0}\frac{Q_i}{Q_0}$$

where n is the number of the collecting annulus; Q_i - the local liquid flow rate in annulus i with face area F_i; F_0 - the column cross section area. The initial liquid superficial velocity distribution, L_i/L_0, where L_i is the local velocity in annulus i, (after a packing layer of 0.15 m) with a distributor case 1, is presented in Fig. 2. The right vertical axis gives the dimensionless wall flow Q_8/Q_0 in the collecting zone VIII adjacent to the column wall, which sums the flow rates of the liquid along the wall and over the annular zone VIII.

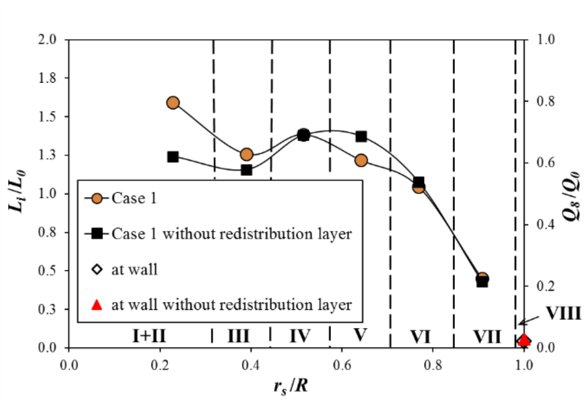


Figure 2. Initial velocity profiles and wall flow - case 1: L_0=7x10^{-3} m^{3}m^{-2}s^{-1}.

The horizontal axis is

$$r_s = \sqrt{\frac{1}{2}\left(R_1^2 + R_2^2\right)}$$

where R_1 and R_2 are inner and outer radius of an annular zone of the column cross section.

Fig. 3 shows that with the liquid distributor case 2 the velocity profiles are more uniform in the whole range of flow superficial velocities. The points show the liquid superficial velocity distribution for 7 liquid loads, while the line presents the mean superficial velocity for all hydrodynamic loads for each annular collecting zone. The mean distribution shows irregularity of ±10% everywhere except for zone VII, where the deviation reaches 21%. The observed irregularity is due to the discrete structure of the packing and the limited width of the collecting zones, moreover no redumping of the packing was applied.

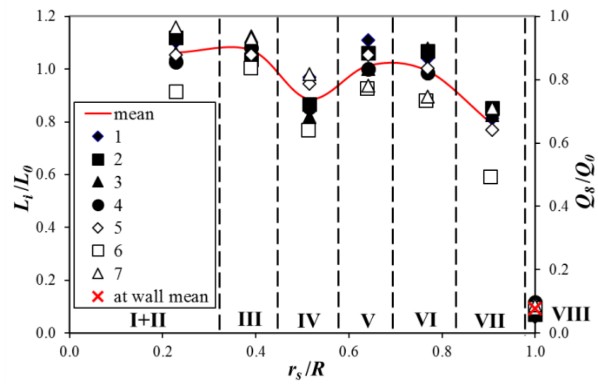


Figure 3. Initial velocity profiles and wall flow - case 2:
1- L_0=3x10^{-3}m^{3}m^{-2}s^{-1}; 2- L_0=4x10^{-3} m^{3}m^{-2}s^{-1}; 3- L_0=5x10^{-3} m^{3}m^{-2}s^{-1}; 4- L_0=7x10^{-3} m^{3}m^{-2}s^{-1};
5- L_0=9x10^{-3} m^{3}m^{-2}s^{-1}; 6- L_0=10x10^{-3} m^{3}m^{-2}s^{-1}; 7- L_0=12x10^{-3} m^{3}m^{-2}s^{-1}.

Model. For cylindrical coordinates (r, z) and axial symmetry, the process of flow distribution in a packed-bed column is described by the following dimensionless equation (Cihla and Schmidt 1957)

$$\left(\frac{\partial^2 f(r,z)}{\partial r^2} + \frac{1}{r}\frac{\partial f(r,z)}{\partial r}\right) = \frac{\partial f(r,z)}{\partial z} \qquad (1)$$

where $r = r'/R$ is dimensionless radial coordinate, r' is radial coordinate, R is column radius, m; $z = Dh/R^2$ is dimensionless axial coordinate; D is liquid distribution coefficient, m; h is axial coordinate, m; $f = L / L_0$ is dimensionless superficial velocity; L, L_0 are local and mean liquid superficial velocity, m^3.m^{-2}s^{-1};

The boundary conditions are the following (Staněk and Kolář 1965):

$$-\frac{\partial f}{\partial r}=B\left(f-CW\right) \quad \text{for r=1.} \qquad (2)$$

$$\frac{\partial f\left(r,z\right)}{\partial r}=0 \quad \text{for r=0} \qquad (3)$$

Parameter B is a criterion for exchange of liquid between the column wall and the packing. Parameter C express the equilibrium distribution of entire liquid flow between the wall and the packing, when equilibrium state is attained $\left(z\to\infty\right)$. W is dimensionless wall flow. The equations defining these parameters are:

$$B=\beta R/D \qquad (4)$$

$$C=\pi R^2\gamma \qquad (5)$$

where β and γ are parameters of boundary conditions, m-2.

The initial conditions (for z = 0) are defined by the type of initial irrigation.

For uniform initial irrigation

$$f\left(r,z\right)=1 \text{ for } 0\le r<1 \text{ and } z=0 \qquad (6)$$

For wall initial irrigation

$$F\,(r,z)=0 \quad \text{for } z=0 \qquad (7)$$

$$W(z)=1 \quad \text{for } z=0 \qquad (8)$$

There are analytical solutions of the above model in the form of infinite series (Staněk and Kolář 1973):

$$f^u(r,z)=A_0+\sum_{n=1}^{\infty}A_n^u J_0(q_n r)\exp\left(-q_n^2 z\right) \qquad (9)$$

$$f^w(r,z)=A_0-\sum_{n=1}^{\infty}A_n^w J_0(q_n r)\exp\left(-q_n^2 z\right) \qquad (10)$$

In the above expressions, f^u(dimensionless) denotes the solution for uniform initial irrigation and f^w (dimensionless) express the corresponding case of wall irrigation. The coefficients are derived from the expressions:

$$A_0=\frac{C}{1+C} \qquad (11)$$

$$A_n^u=\frac{2\left(q_n^2/B-2C\right)}{\left[\left(q_n^2/B-2C\right)^2+q_n^2+4C\right]J_0\left(q_n\right)} \qquad (12)$$

$$A_n^w=\frac{2\left(q_n^2/B-2C\right)}{\left[\left(q_n^2/B-2C\right)^2+q_n^2+4C\right]J_0\left(q_n\right)} \qquad (13)$$

The dimensionless wall flows W^u and W^w are calculated from Eqs. (9), (10), and from the material balance given below:

$$W^u=\frac{1}{1+C}-2\sum_{n=1}^{\infty}A_n^u\left(q_n\right)\frac{J_1\left(q_n\right)}{q_n}\exp\left(-q_n^2 z\right) \qquad (14)$$

$$W^w=\frac{1}{1+C}+2\sum_{n=1}^{\infty}A_n^w\left(q_n\right)\frac{J_1\left(q_n\right)}{q_n}\exp\left(-q_n^2 z\right) \qquad (15)$$

where J_0, J_1 are Bessel functions of the first kind, zero and first order; q_n are roots of the following equation:

$$\left[\left(2C/q_n\right)-\left(q_n/B\right)\right]J_1\left(q_n\right)+J_0\left(q_n\right)=0 \qquad (16)$$

In this paper we propose the following scheme for parameters' estimation of the mathematical model described above.

1) Parameter C can be determined from experimental values of the dimensionless flow rates in the liquid collecting device (LCD), as was proposed by Staněk and Kolář (1968). The following formulas have been developed for calculation of C; the second one concerning the case when wall flow is collected and measured in the last annular section of the LCD together with flow rate, corresponding for this section:

$$C=\frac{Q_i^w\left(r_i,r_{i-1}\right)}{r_i^2-r_{i-1}^2-Q_i^u\left(r_i,r_{i-1}\right)} \qquad (17)$$

for annular section of LCD i = 1, k-1,

$$C=\frac{1-Q_i^w\left(r_i,r_{i-1}\right)}{Q_i^u\left(r_i,r_{i-1}\right)-\left(r_i^2-r_{i-1}^2\right)} \qquad (18)$$

for last annular section of LCD $i=k$,

where r_i, $Q_i^{u,w}$ are dimensionless inner radius and dimensionless flow rate, measured in each section of LCD.

The value of C has been determined by Eqs. (17) and (18) and experimental data for dimensionless flow rates in the VII and VIII sections of LCD at uniform and wall irrigation, from two parallel redumpings of packing layer. The obtained value is $C = 0.9811$.

2) The value of the spreading coefficient D is given from results of tracer method, developed by Dzhonova et al. (2007) for investigated packing RSRM 1.5", namely $D = 0.0024\text{m}$.

3) Then, only parameter B can be identified by non-linear optimization, minimizing the residual variance:

$$S_A^2 = \frac{1}{k-1}\sum_{i=1}^{k} n_i\left(f_{ie} - f_{ic}\right)^2 \qquad (19)$$

where f_i is the mean dimensionless density of irrigation in i-th annular section of the column cross section (i=1÷8), delimited by the radii r_{i-1} and $r_i\left(r_i > r_{i-1}\right)$ and is determined by the expression

$$f_i = \frac{2}{r_i^2 - r_{i-1}^2}\int_{r_{i-1}}^{r_i} f(r,z)rdr$$

with indices "e" and "c" denoting experimental and calculated values.

4) After fixing the global minimum of S_A^2 and the respective value for B, the model adequacy is tested by Fisher criterion

$$F = \frac{S_A^{2\min}}{S_0^2} < \chi_{1-\alpha}^2\left(m, m'\right) \qquad (20)$$

for χ^2- distribution with degrees of freedom $m = k-1$ and $m' = n-k$ for probability $1-\alpha$.

Here the reproductive variance S_0^2 of experimental data is obtained from:

$$S_0^2 = \frac{1}{n-k}\sum_{i=1}^{k}\left(n_i - 1\right)S_i^2 \qquad (21)$$

5) For the calculations, the experimental packing height H=0.6 m is corrected according to the following considerations.The packed bed is irrigated by multipoint liquid distributor with spray orifices arranged uniformly along the apices of equilateral triangles. The number of the orifices (as mentioned above) is 85, the distance between them is 48 mm except 12 peripheral points lightly moved to avoid the formation of parasitic wall flow. To achieve given uniformity of liquid distribution some redistribution packing bed is needed. For determination of the height (h_r) of the redistribution bed the following simplified formula can be used (Semkov 1991):

$$h_r = \frac{a^2}{D}\left[0.04468 - 0.02270\ln\left(\frac{L_{\max} - L_{\min}}{L_0}\right)\right] \qquad (22)$$

where a is the distance between the orifices in triangular arrangement, m; L_{max}, L_{min} and L_0 are the maximum, minimum and mean irrigation density, respectively, $m^3m^{-2}s^{-1}$.Then in the present case (a = 48 mm, D = 0.0024 m for RSRM 1.5") and 10% irregularity h_r = 0.093 m. This height is excluded from the experimental packing height applying the mathematical modeling for parameter optimization.

Results and Discussion

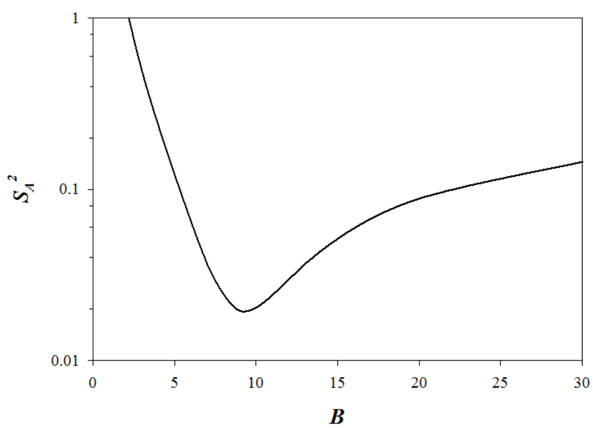
Results for parameters' identification and adequacy test. All calculation are made with specially developed software that includes: resolution of model equations, nonlinear optimization with Newton - Raphson method, comparison of experimental and theoretical values for the collecting annuluses, determination of theoretical profile of the local irrigation density. The optimal value of B is found to be 9, for minimal value of .

The experimental data for the mean-integral density of irrigation for annuluses I-VIII, for two types of initial irrigation, as well as the corresponding calculated values at the determined values of the parameters B, C and D, and the relative discrepancy are given in Table 1.

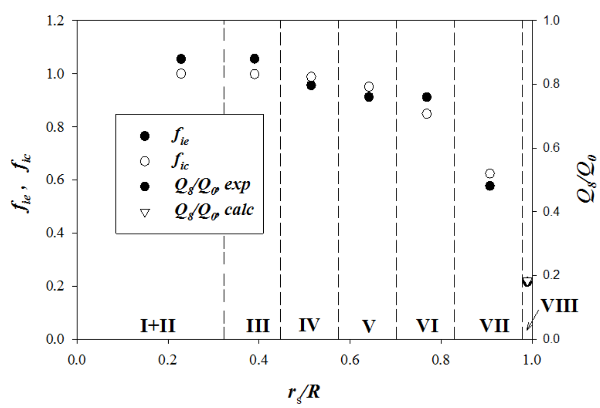
Table 1. The experimental data for the mean-integral density of irrigation for annuluses I-VIII.

Number of annulus	I+II	III	IV	V	VI	VII	VIII*
f_{ie}	1.060	1.060	0.956	0.912	0.911	0.577	0.179*
f_{ic}	0.999	0.998	0.988	0.951	0.849	0.624	0.183*
$\delta,\%$	6.0	6.2	-3.2	-4.1	7.3	-7.5	-2.0

* Values computed on the basis of the flow rate into annulus VIII plus wall flow W^u. It is made to decrease the errors caused by the relatively small surface area of annulus VIII.
δ is the relative discrepancy.



(a)



(b)

Figure 4. Results: (a) from identification of model parameter *B*; (b) comparison between theory and experiment for RSRM 1.5".

Fig. 4a visualizes optimization results for B = 9. Fig. 4b shows in dimensionless values the irrigation density and its mean-integral values (theoretical and experimental) related to the radius of column segments (dimensionless).

As it is seen from Fig. 4b, the comparison between experimental and theoretical mean dimensionless density of irrigation in all annular sections of the column cross section is quite well. In the last, VIII section, they are given as dimensionless flow rates and are related to right ordinate scale. The experimental results for uniform irrigation are averaged for 3 redumpings and 7 hydrodynamic loads in the mentioned range.

The optimization procedure, mentioned above, results in the following values of the parameters B=9, C=0.9811, D=0.0024m at $\min(S_A^2)=0.0107$ with volume $m=k-1=6$, and $S_0^2=0.0299$ with $m'=n-k=14$, gives that the model is adequate at significance level α =0.05:

$$F=\frac{\min\left(S_A^2\right)}{S_o^2}=0.357<F\left(6.14\right)=2.85$$

Conclusions

The present study fills the gap in experimental data for liquid velocity profiles in a semi –industrial packed column with a RSRM packing. It offers measures for improving the initial uniformity, which is evaluated by maldistribution factor.

The proposed identification method can be successfully applied for determination of the parameters B and C in the boundary conditions simultaneously, if we have information about the coefficient of liquid distribution D. It is necessary to carry out experiments with uniform initial liquid distribution and collection of the liquid in multisectional collecting device. New formulae are proposed for determination of C in the case when wall flow is not measured at both uniform and wall initial irrigation.

The authors have not found other attempts to apply the presented approach for modeling the liquid distribution in a layer of random RSRM packing, which is characterized with “open to flow structure”. As reported in Dzhonova et al. (2007), these types of packings have many lamellas and distribute liquid flow randomly, on the contrary to the previous generations of older types of packings like Raschig rings, which radial redistribution ability is higher than RSRM.

Acknowledgments

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