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Experimental Investigation of Liquid Distribution in Open-structure Random Packings as a Basis for Model Refinement

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The present study aims at investigation of the liquid phase distribution in order to fill in the missing data on liquid spreading in industrial scale packing layer of metal Raschig Super-Ring (RSR) packings for development of a reliable prediction model. Our attempt to apply the well-proven dispersion model to RSR packings has faced difficulties connected with the packing open, web-like structure resulting in poor radial distribution properties and with the industrial scale of the packed column. An experimental set-up is designed so as to provide the necessary data for model parameters’ identification. Special attention is paid to the uniform liquid distributor, in order to ensure the validity of the model assumption of regular initial irrigation. The approach avoids the need of data from well-established wall flow, which can be measured at a very high (over 3 m in that scale) packing layer. Instead, it uses additional data from irrigation on the column wall, provided by a peripheral liquid distributor. The present work has obtained original data for the liquid distribution in RSR packings of different sizes addressing improvement and validation of a prediction model.

1. Introduction

Packed columns are typical apparatuses for separation processes in gas-liquid systems. They are largely used for absorption of harmful compounds from waste gases from power and chemical industry for distillation in fuel, food and pharmaceutical production and for waste heat utilization (Kolev, 2006). Very intensive research area with importance for environment protection is enhancement of technologies for post combustion absorption of CO_2 and SO_2. New absorbents are studied for CO_2 capture (Langa et al., 2017) and methods for SO_2 removal are evaluated (Dzhonova et al., 2013).

Modern high performance packings ensure efficient mass transfer by large interfacial area and flow turbulization at low pressure drop. However the uniform radial distribution of the flows is of great importance for achieving the maximal efficiency.

Our work aims at experimental investigation of the liquid spreading and the wall flow in a bed of random metal Raschig Super-Ring packing widely employed in absorption and rectification processes (Schultes, 2003). It fills the gap in liquid distribution data for this type of packings. The obtained results are used in (Petrova et al., 2018) as a base for development of a new procedure to identify the parameters in a mathematical model.

2. Dispersion model

For describing the liquid distribution in random RSR packings (Figure 1), a well-proven approach with a dispersion model is employed, Eq(1) (Cihla and Schmidt, 1957):

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

where $f = L/L_0$ stands for a dimensionless superficial velocity, $z = Dh/R^2$ and $r = r'/R$ are dimensionless coordinates; r' is a radial coordinate, m; R is a column radius, m; D is a packing liquid spreading coefficient, m;

h is an axial coordinate, m; L_0 is a mean liquid superficial velocity determined as the feed flow rate divided by the total column cross-section area, $m^3/(m^2s)$; L is a local liquid superficial velocity, $m^3/(m^2s)$.
This equation is solved at the following boundary conditions (Staněk and Kolář, 1965):

$$r = 1 \quad -\frac{\partial f}{\partial r} = B(f - CW) \tag{2}$$

$$r = 0 \quad \frac{\partial f(r,z)}{\partial r} = 0 \, , \tag{3}$$

where W denotes a dimensionless wall flow, which is the flow rate down the wall divided by the feed flow rate in the column.
The application of this model to RSR packings has faced difficulties connected with the semi-industrial scale of the column and the specific open structure of the packings leading to low radial spreading. A procedure overcoming these difficulties is proposed in a previous work (Dzhonova et al., 2018) for identification of the parameters B, C and D in the analytical solution. It comprises the following steps.
The value of the spreading coefficient D is taken from the results of an experimental method, developed by Dzhonova et al. (2007).
The parameter C expresses the equilibrium distribution of the total liquid flow between the wall and the packing at equilibrium state ($z \to \infty$). Stanék and Kolář (1973) proposed a method to avoid measurements at a high packing layer necessary for equilibrium flow state. They used experimental data for radial liquid distribution under a packing layer at two types of irrigation at the top of the column, uniform and wall irrigation. Following their approach, measurements are performed with a liquid collector consisting of 8 concentric annular sections under the packing layer (Figure 2). The value of C is determined with the obtained data by Eq(4) and Eq(5):

$$C = \frac{M^w(r_{i-1}, r_i)}{r_2^2 - r_1^2 - M^u(r_{i-1}, r_i)} \tag{4}$$

for these annular sections, VI–VII (Figure 2), where sensitivity of the liquid distribution to the values of C and B is observed. Here r_{i-1} and r_i are the inner and outer radii of a collecting annulus, where i is the annulus number;

$$C = \frac{1 - M^w(r_{i-1}, r_i)}{M^u(r_{i-1}, r_i) - (r_i^2 - r_{i-1}^2)} \tag{5}$$

for the last annular section adjacent to the column wall, i = 8.
The quantity $M^w(r_{i-1},r_i)$ is a fractional dimensionless flow rate between r_{i-1} and r_i at wall initial irrigation (marked by superscript w) defined as

$$M^w(r_{i-1}, r_i) = \int_{r_{i-1}}^{r_i} r f^w \, dr \tag{6}$$

$M^u(r_{i-1},r_i)$ is a fractional dimensionless flow rate between r_{i-1} and r_i at uniform initial irrigation (marked by superscript u), defined by analogous equation. The values of $M^w(r_{i-1},r_i)$ *and* $M^u(r_{i-1},r_i)$ *are* measured in each annulus i = 1–8, presented in Section 4.
The parameter B is a criterion for exchange of liquid between the column wall and the packing. It is evaluated by fitting the theoretical and experimental profiles of the liquid superficial velocity and minimizing the sum of square deviations.

3. Experimental set-up and methods

Figure 1 shows the investigated random metal RSR packing. Three packing element sizes are studied RSR 0.7, RSR 1.5 and RSR 3. The main unit of the experimental installation is a steel semi-industrial column with a diameter of 0.470 m, detailed scheme presented in (Dzhonova et al., 2014). The height of the packing layer is 0.6 m. The measurements are performed by means of a liquid collecting method with an annular liquid collector, Figure 2, placed under the packing layer. A single phase flow of tap water at a room temperature, is fed at the top of the column. The flow rate in each annulus is measured by the volume of the liquid collected in it per unit time. The wall flow is collected in a 5 mm wide annulus next to the column wall. The necessary two types of initial liquid distribution, uniform and wall distribution, are provided by using two types of liquid distributors, uniform and peripheral, Figure 3.

Figure 1: Raschig Super-Ring packing (Raschig GmbH catalogue)

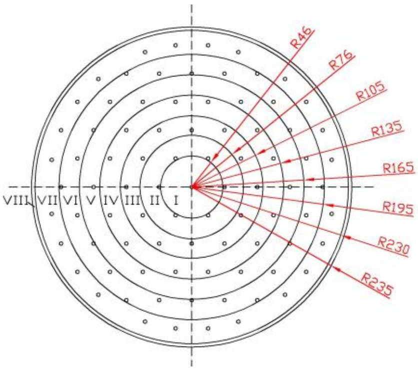


Figure 2: Annular liquid collector under the packing and feed points' projections of the uniform liquid distributor

Special attention is paid to the uniform liquid distributor in order to ensure the validity of the model assumption of uniform initial velocity profile. Details are described in (Dzhonova et al. 2018). The measurements with uniform initial liquid distribution are performed at liquid feed flow rates Q_0 = 1.87–7.49 m^3/h (mean liquid superficial velocity $L_0 = 3\cdot10^{-3}$–$12\cdot10^{-3}$ $m^3/(m^2s)$). Data for liquid distribution are obtained also with wall irrigation at liquid feed flow rates down the wall Q_0^w = 0.3–0.6 m^3/h.

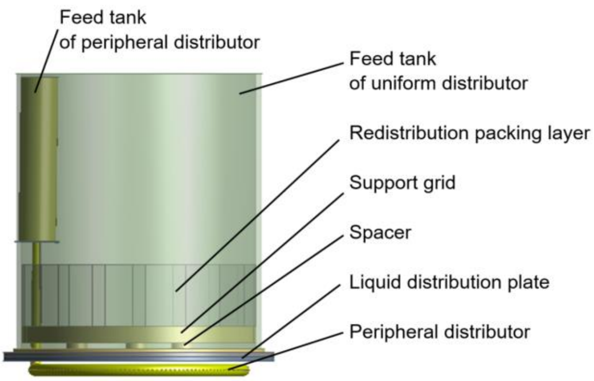


Figure 3: Uniform and peripheral liquid distributors

4. Results and discussion

4.1. Superficial velocity distribution

Figure 4 presents the experimental superficial velocity distribution at a packing height of 0.6 m versus radial coordinate *r*. The inner and outer radii of the annular collecting sections are marked by dashed lines. The value of the dimensionless radial coordinate r_{si} corresponding to the value of the local liquid superficial velocity over the cross-section area of a collecting annulus *i* is determined as a quadratic mean radius (Tour and Lerman, 1944):

$$r_{si} = \sqrt{\frac{1}{2}(r_{i-1}^2 + r_i^2)} \tag{7}$$

Each data point is a mean value from three reloadings of the packing layer. It is seen that in collecting sections I-V the uniformity is approximately preserved, the dimensionless superficial velocity in that region is close to unity. This is common in large scale columns, as can be seen in (Yin, 1999) for a 0.6 m column diameter and (Hanusch et al., 2017) for a 1.2 m column diameter. Only the region near the wall, comprising collecting sections VI-VIII, shows irregularity due to the spreading ability of the packing and the formation of a wall flow. This peculiarity raises difficulties in identification of the model parameters, since a great part of the measured profile gives no information for the radial liquid spreading. The dispersion model was first developed using data from small scale experimental columns, where no such uniform central region was present.

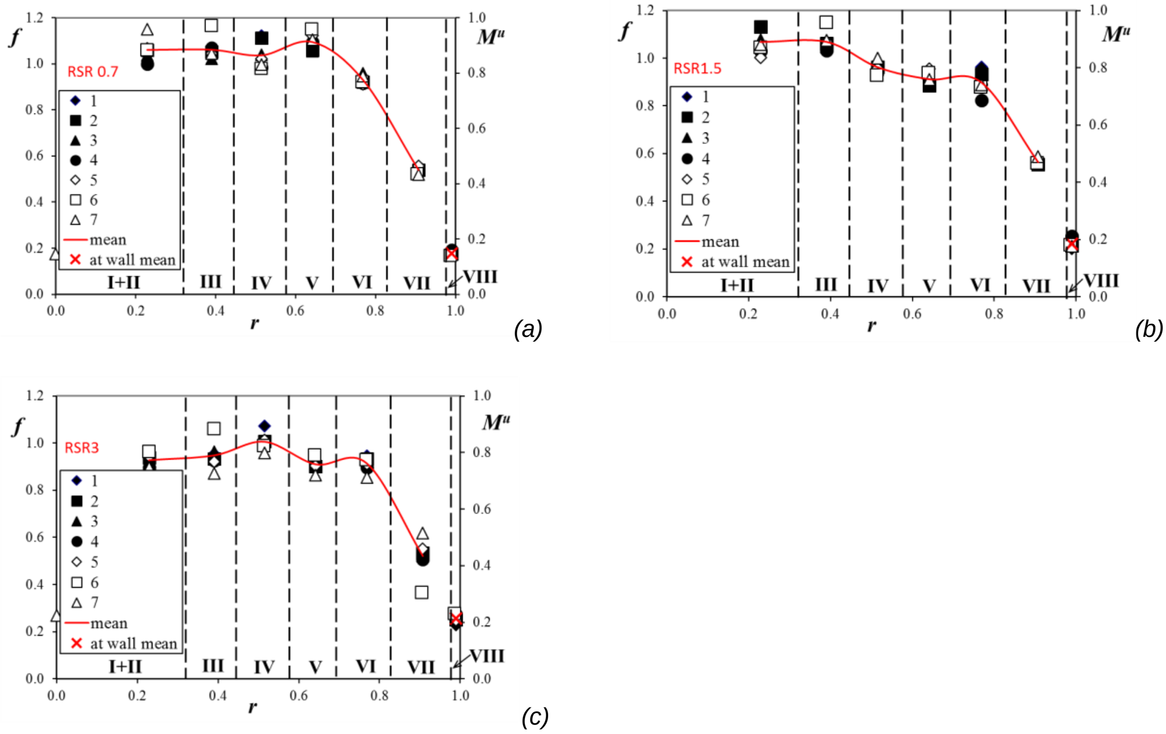
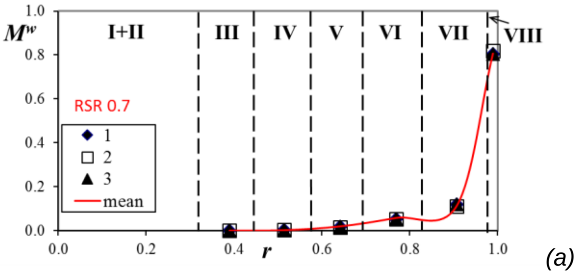
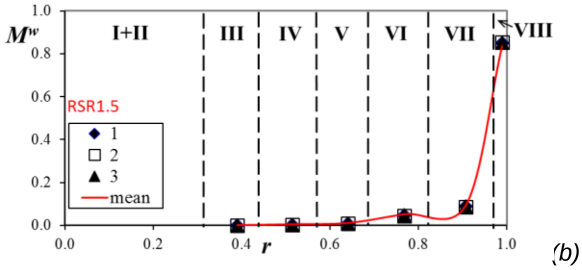


Figure 4: Liquid superficial velocity profiles and wall flow at uniform irrigation. Packing layer height 0.6 m, packing sizes (a) RSR 0.7, (b) RSR 1.5, (c) RSR 3; 1- $L_0 = 3 \cdot 10^{-3}$ $m^3/(m^2s)$, 2- $L_0 = 4 \cdot 10^{-3}$ $m^3/(m^2s)$, 3- $L_0 = 5 \cdot 10^{-3}$ $m^3/(m^2s)$, 4- $L_0 = 7 \cdot 10^{-3}$ $m^3/(m^2s)$, 5- $L_0 = 9 \cdot 10^{-3}$ $m^3/(m^2s)$, 6- $L_0 = 10 \cdot 10^{-3}$ $m^3/(m^2s)$, 7- $L_0 = 12 \cdot 10^{-3}$ $m^3/(m^2s)$

The secondary axis on the right (M^u) in Figure 4 is refers only to the points in annulus VIII of the fractional dimensionless flow rate M^u, which is necessary for calculating the model parameter *C* by Eq(5). The flow rate measured in the annulus VIII includes the flow rate on the wall and a small component over the 5 mm wide annular cross-section. The measured superficial velocity profiles *f* in Figure 4 are necessary for the evaluation of the model parameter *B*, Section 2. Figure 4 shows a slight increase in the wall flow with the packing size from 0.15 (RSR 0.7) to 0.21 (RSR 3). As expected, the liquid distribution is independent of the total flow rate at that experimental error. The data for an individual feed flow rate deviates from the mean by a maximal relative difference of about 10 %. The observed maximal deviation from the mean in a reloading of the packing is of the same magnitude. The experimental deviations are due to the reloading of the packing, since the error of parallel measurements without reloading is very small (under 2 %) and can be neglected.

Figure 5 presents the distribution of the fractional dimensionless flow rate (M^w) at peripheral irrigation on the column wall, necessary for evaluation of *C*, Eq(4) and Eq(5). The data is averaged for three reloadings and exhibits again an increase in the wall flow with the packing size from 0.81 (RSR 0.7) to 0.88 (RSR 3).





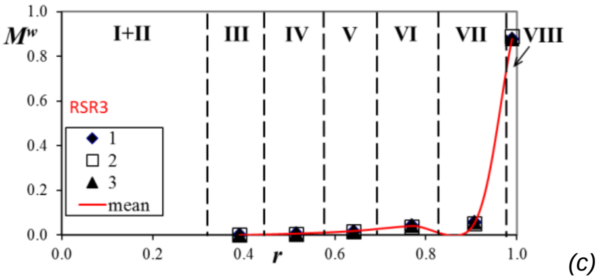


Figure 5. Fractional dimensionless liquid flow rate distribution in peripheral irrigation. Packing layer height 0.6 m, packing sizes (a) RSR 0.7, (b) RSR 1.5, (c) RSR 3. 1- $Q_0^w = 0.3$ m³/h, 2- $Q_0^w = 0.45$ m³/h, 3- $Q_0^w = 0.6$ m³/h.

4.2. Liquid maldistribution factor

It is worth to evaluate the uniformity of the liquid distribution using a maldistribution factor in the form introduced by Hanusch et al. (2017):

$$M_f = \frac{1}{F_0}\sum_{i=1}^{n} F_i \left|\frac{L_i - L_0}{L_0}\right| \quad (8)$$

where F_i and F_0 are the cross-section area of a collecting annulus *i* and the total cross-section area of the column, m^2. $M_f = 0$ –perfectly uniform distribution, $M_f = 2$ –worst possible in packed columns (Hanusch et al., 2017).

In Figure 6 the value of M_f slightly increases with the total column load. This tendency is more apparent for RSR 3, while for the smaller packings it is negligible. Figure 6 shows that the maldistribution factor increases with the packing size, which can be explained by the increase in the wall flow for bigger element size, commented in section 4.1. The observed influence of the liquid load and the packing size on the values of M_f are in conformity with the data in (Hanusch et al., 2017), where the authors reported a maldistribution factor from 0.22 to 0.38 at industrial conditions for Rauschert Metal Saddle Rings (RMSR) 70-5, which also belong to the group of open-structure random packings.

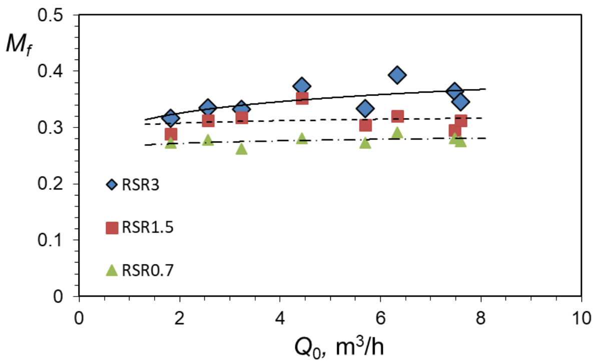


Figure 6: Maldistribution factor versus liquid load at a packing layer height of 0.6 m for packing sizes RSR 0.7, RSR 1.5, RSR 3

5. Conclusions

The present experimental study fills the gap in liquid distribution data for a semi-industrial packed column with a RSR packing. The results show that at a given packing size the liquid superficial velocity profiles are independent of the liquid load. It is observed that the increase in the packing size leads to deterioration of the distribution uniformity due to an increase in the wall flow. This effect corresponds to the obtained higher values of the maldistribution factor for bigger packing element sizes. It is found that in the regimes under investigation the liquid load increase leads to a slight increase in the liquid maldistribution factor for the biggest element size RSR 3. The semi-industrial experiment obtains new data for development and validation of a dispersion model of liquid spreading in RSR packings.

Acknowledgments

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