

MODELING OF LIQUID SPREADING IN RANDOMLY PACKED METAL PALL RINGS

МОДЕЛИРАНЕ НА РАЗТИЧАНЕТО В НЕНАРЕДЕНИ МЕТАЛНИ ПРЪСТЕНИ НА ПАЛ

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Abstract: The present work compares two different approaches, Computational Fluid Dynamics (CFD) and dispersion model, for liquid distribution modeling with experimental data for liquid spreading in randomly packed metal Pall rings. The used experimental data are obtained in a semi-industrial column with a 0.6m diameter for several packing heights and liquid loads. It is shown that the appropriate choice of dispersion model parameters is essential for prediction of liquid distribution. In both models some parameters are determined by fitting with experimental data, the remainder are calculated or taken from literature. Comparison of the two model liquid distributions with experimental data shows that both CFD and dispersion model are in good agreement with the experiment especially for higher packing bed, when the wall flow is fully developed.

Keywords: PACKED-BED COLUMN, LIQUID DISTRIBUTION, RANDOM PACKING, DISPERSION MODEL, PARAMETER IDENTIFICATION

1. Introduction

Packed columns are widely used for separation processes such as rectification and absorption in chemical industry and environmental protection due to their high efficiency at low pressure drop. The recent interest is connected with technologies for flue gas scrubbing, heat recovery and fuel production. The uniform liquid distribution in the packed bed cross-section is crucial for the efficiency of the transfer processes. Several models are proposed to predict the liquid distribution in a packed bed starting from the random walk model of Tour and Lerman [1] for liquid spreading in unconfined packing with no wall effect and the dispersion model of Cihla and Schmidt [2] developed by other authors to account for the wall flow. Lately the techniques of Computational Fluid Dynamics (CFD) are widely employed for prediction of the liquid distribution by treating the packing bed as a porous media with permeability resistance, Yin [3], or by reconstructing the geometry of the packing bed and tracking the gas-liquid interface area.

The present work compares results from a dispersion model and a CFD simulation of liquid spreading in a packed bed of random Pall rings.

2. Model description

In this part a brief concept of dispersion model equations, boundary conditions, and solution is presented. The full description is given in the work [4]. The process of flow distribution in a packed-bed column is described by the following dimensionless equation [2]:

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

where $r = r'/R$ is dimensionless radial coordinate; r' is radial coordinate, m; 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, $m^3/m^2 \cdot s$. The boundary conditions are the following [5]:

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

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

where parameter B is a criterion for exchange of liquid between the column wall and the packing; parameter C expresses the equilibrium distribution of entire liquid flow between the wall and the packing when equilibrium state is attained $z \rightarrow \infty$; W is dimensionless wall flow.

The equations defining these parameters are:

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

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

where β , γ , and $1/m^2$, are parameters in the boundary conditions.

At $z = 0$ the uniform initial irrigation is defined as:

$$(6) f(r, z) = 1, \text{ for } 0 \leq r < 1 \text{ and } z = 0$$

There is analytical solution of the above model in the form of infinite series [6]:

$$(7) f^u(r, z) = A_0 + \sum_{n=1}^{\infty} A_n^u J_0(q_n r) \exp(-q_n^2 z),$$

In the above expressions, f^u (dimensionless), denotes the solution for uniform initial irrigation. The coefficients are derived from the expressions:

$$(8) A_0 = \frac{C}{1+C}, \quad A_n^u = \frac{2(q_n^2 / B - 2C)}{\left[(q_n^2 / B - 2C)^2 + q_n^2 + 4C \right] J_0(q_n)},$$

The dimensionless wall flow W^u is calculated from Eq. (9) and from the material balance:

$$(9) W^u = \frac{1}{1+C} - 2 \sum_{n=1}^{\infty} A_n^u(q_n) \frac{J_1(q_n)}{q_n} \exp(-q_n^2 z),$$

where J_0, J_1 are Bessel functions of the first kind, zero and first order; q_n are the roots of the characteristic equation, following from boundary condition (2):

$$(10) [(2C/q_n) - (q_n/B)] J_1(q_n) + J_0(q_n) = 0$$

3. Experimental data.

Experimental data for the liquid distribution in a column filled with metal Pall rings, of 25 mm, used in this paper are taken from the PhD thesis of Yin [3]. They are obtained in a pilot column with 0.6m diameter, for packing heights 0.9 and 3.0 m, and liquid and gas loads $L = 2.91; 4.78; 6.66, G = 0; 0.75 \text{ kg/m}^2 \cdot \text{s}$. The liquid collecting device consists of 6 segments, the initial irrigation is uniform.

4. Methods of estimation and identification of model parameters

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

1) The value of C can be determined even if there are not available data for wall initial irrigation. In this case the data about wall flow at several packing heights for uniform initial irrigation are needed. We use the relation (9) in the limiting case when $z \rightarrow \infty$; as it is seen, the last term in (9) diminishes and the result is:

$$(11) W^u \Big|_{z \rightarrow \infty} = \frac{1}{1+C},$$

2) In this work the value of the radial spreading coefficient D is taken from the literature [7];

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

$$(12) S_A^2 = \frac{1}{k-1} \sum_{i=1}^k n_i (f_{ie} - f_{ic})^2,$$

where f_i is the mean dimensionless density of irrigation in i -th annular section of the liquid collecting device, delimited by the radii r_{i-1} and r_i ($r_i > r_{i-1}$) and is determined by the expression

$$(13) f_i = \frac{2}{r_i^2 - r_{i-1}^2} \int_{r_{i-1}}^{r_i} f(r, z) r dr,$$

with indices "e" and "c" denoting experimental and calculated values of liquid density of irrigation.

As explained above, three parameters should to be determined – C, D and B . In the light of experimental data used in this paper, for calculation of C eq. (11) is used. Then, the obtained value for C is 5.95, which is very close to the value ($C = 5.29$), obtained for ceramic Pall rings 25 mm in [4]. Here, the value of C is calculated from the results [3] for the wall flow at uniform initial irrigation for packing heights 0.9, 1.8 and 3.0 m at liquid load $L = 6.66 \text{ kg/m}^2 \cdot \text{s}$ and no gas flow, because at these conditions a fully developed wall flow is achieved. As it is recommended in [8], the value of C is better to obtain from data at higher packing layer, when the equilibrium between bulk zone and wall flow is reached. On the contrary, these authors mentioned, that the parameter B has to be identified/calculated

for lower packing depths, because at higher ones it loses its importance.

In this work the value of D is chosen to be $D = 0.0007 \text{ m}$. This value is the last result [7], reported in the literature about metal Pall rings, 25.4 mm, and, which is more important, the results of Wen et al.[7] are obtained for the same packing, as in [3]. The previous reported data for D is that of Stikkelmann [9], which is about 3 times larger (0.0025m) although the method of calculating of D is the same as in the work [7]. The probable explanation of these differences in the value of D is that a piece of Pall ring packing may have different geometry inside its cylindrical body – see [10]. The Pall rings are created in 1940 and up to now a large number of manufacturers as well as many modifications of this packing type exist (Flexiring, Raflux ring, P-ring, Hy-pak, etc.). The cut "windows" in one packing element may have different width and curvature, which changes the radial spreading inside the packing element, and this result in a large variety of spreading coefficients even for the same packing diameter and material [11]. In [4], the reported value for ceramic Pall rings, 25 mm, for approximate comparison, is $D = 0.0011 \text{ m}$, but the inside geometry of ceramic Pall rings is different from that of metal one.

The only one model parameter to be identified is B . That is done using the minimal residual variance (12) between model and experimental mean dimensionless density of irrigation (13) in each segment of liquid collecting device (detailed procedure is described in [12]). The obtained value is $B = 25$.

4. Comparison of liquid predictions (CFD results of Yin [3] and current model) with experimental data for metal Pall rings [3]

In [3], the comparison between experimental and CFD data for liquid relative velocity is made, for packing heights $H=0.9 \text{ m}$ and $H=3.0 \text{ m}$, for $L=4.78 \text{ kg/m}^2 \cdot \text{s}$ and $G=0.75 \text{ kg/m}^2 \cdot \text{s}$, which is below the reported loading point and the influence of the gas phase is not significant. We compare these results with model solution (7) for already identified values of the parameters. The comparison of both model predictions - CFD and dispersion model from this work are presented in figures 1 and 2.

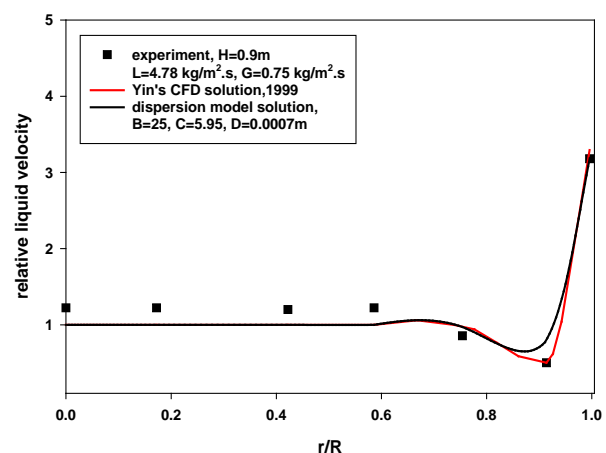


Fig. 1 Comparison of relative liquid velocities between dispersion model predictions, Yin's CFD predictions and Yin's experimental data: $L=4.78 \text{ kg/m}^2 \cdot \text{s}$; $G=0.75 \text{ kg/m}^2 \cdot \text{s}$; for packing height $H=0.9 \text{ m}$.

As can be seen, both models describe very well experimental data. For lower packing height the radial profile of experimental data in the bulk zone are still parabolic and equalize when the packing height is increased. Both predictions are more accurate at $H=3.0 \text{ m}$.

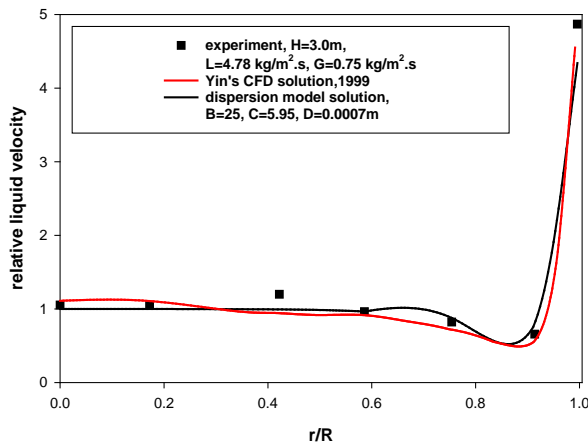


Fig. 2 Comparison of relative liquid velocities between dispersion model predictions, Yin's CFD predictions and Yin's experimental data: $L=4.78 \text{ kg/m}^2\cdot\text{s}$; $G=0.75 \text{ kg/m}^2\cdot\text{s}$; for packing height $H=3.0 \text{ m}$.

It should be mentioned, that at both figures, model predictions of [3] are performed with the aid of the modern CFD package CFX4.2. Two of the parameters, included in the closure equations and relations, also were obtained by fitting with the experiment. They are connected with 'liquid dispersion coefficient', defined by Yin [3] for volume average concept, and turbulent term, included in it.

In the case of no gas flow, in the next figures 3 and 4, the results of dispersion model predictions for the same heights, but for different liquid loads $L=2.91 \text{ kg/m}^2\cdot\text{s}$ and $L=6.66 \text{ kg/m}^2\cdot\text{s}$ are also presented. For above identified model parameters the coincidence between the model and experiment is quite well, which is additional verification of dispersion model ability to predict liquid spreading in packed beds.

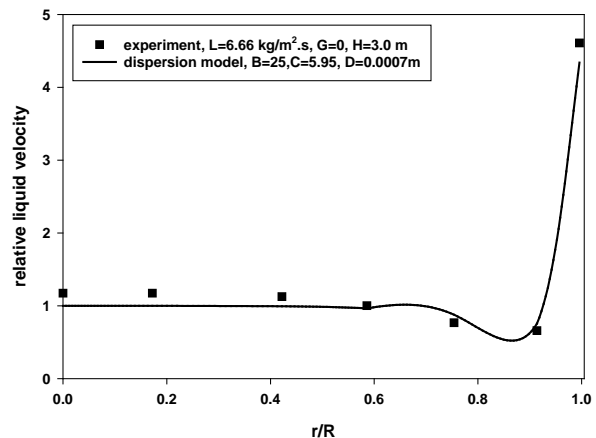
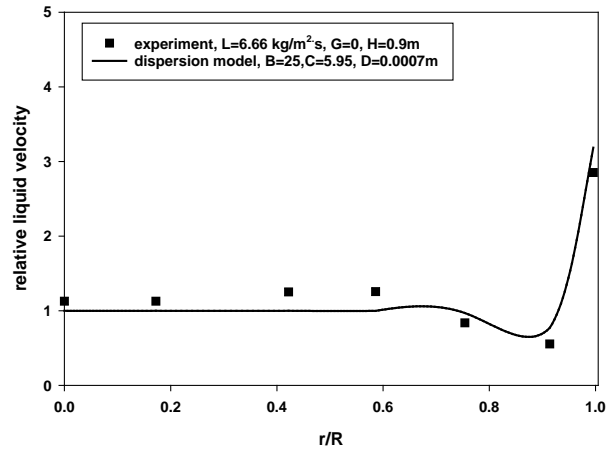


Fig. 4 Comparison of relative liquid velocities between dispersion model predictions and Yin's experiment: $L=6.66 \text{ kg/m}^2\cdot\text{s}$; $G=0$; for packing heights $H=0.9 \text{ m}$ (up) and $H=3.0 \text{ m}$ (down).

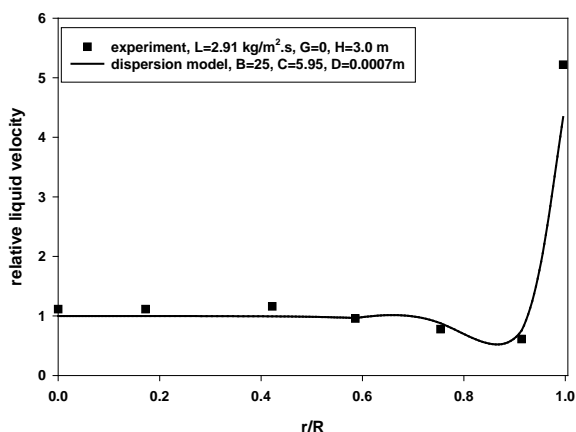
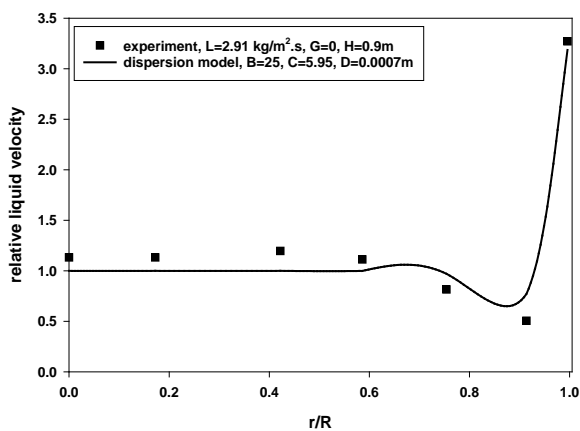


Fig. 3 Comparison of relative liquid velocities between dispersion model predictions and Yin's experiment: $L=2.91 \text{ kg/m}^2\cdot\text{s}$; $G=0$; for packing heights $H=0.9 \text{ m}$ (up) and $H=3.0 \text{ m}$ (down).

5. Conclusions

In the current work the results of dispersion model prediction for liquid distribution in random packing and identification procedure for model parameters are presented. A new formula is proposed for estimation of model parameter C in the case of uniform initial irrigation only, and experimental data for liquid distribution at several packing layer heights. Validation of model prediction for identified model parameters with experimental data of [3] for Pall rings, at two different packing heights and three liquid loads shows, that dispersion model analytical solution could be used successfully for fast prediction of liquid distribution in randomly packed beds.

The dispersion model results are also compared with CFD prediction and experimental data of Yin for liquid distribution in a packed bed with metal Pall rings [3]. Comparison of two theoretical liquid distributions with experimental one show, that both describe very well the experimental data.

6. Literature

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