THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE FUNCTION OF THE WALL FLOW DEFLECTING RING. A SINGLE RING

Vladimír STANĚK[a], Krumm SEMKOV[b], Nikolai KOLEV[b] and Georgii PASKALEV[b]

[a] *Institute of Chemical Process Fundamentals, Czechoslovak Academy of Sciences, 165 02 Prague 6 - Suchdol, Czechoslovakia and*
[b] *Central Laboratory of Chemical Process Fundamentals, Bulgarian Academy of Sciences, Sofia 1113, Bulgaria*

Received March 12th, 1984

Theoretical model has been formulated of the flow of liquid in a randomly packed trickle bed column equipped with special wall flow deflecting rings (WFDR). Solutions have been obtained of the model for the case of a single ring. Theoretical results have been compared with experimental distributions of liquid in a 188·6 mm in diameter column packed with 25 mm Raschig rings and equipped with a single WFDR.

Reasonable agreement of the theory with experimental results has been found and the theory is felt to be important in the future for optimizations of the number, size and spacing of the WFDR's to be used in industrial columns to check the extent of the flow on the wall.

It has been well established[1] that the mass transfer coefficients in industrial size packed bed columns reach values substantially lower than those determined on the basis of data from laboratory scale columns. This observation may be accounted for[2] by nonuniform distribution of phases over the cross sectional area of the column and primarily the nonuniformities of the liquid phase flow.

One of the principal factors contributing to the nonuniform distribution of liquid is its tendency to flow toward the column wall to form here the wall flow. The mechanism of liquid distribution has been investigated by several authors[3-10]. Methods also have been proposed for the calculation of the magnitude of the wall flow as well as the local density of irrigation in the column.

To check the wall flow formation Stürman[11] as early as in 1936 proposed modification of the column wall. The aim of the modifications was to achieve the same distribution of packing pieces in the proximity of the wall and in the bulk of the layer. The modifications involved installations of horizontal fins on the wall, corrugated surface of the wall or hemispherical protrusions on the wall. The investigations of Kirschbaum[12], carried out in a column with corrugated walls, showed that the height of a transfer unit did not depend on the height of the packed section. This indirectly confirms the absence of the wall flow effects. Regardless of the type of the modification of the wall proposed by Stürman it was concluded in the literature[13] that from the standpoint of the economy such modifications are ineffective.

The literature[14] provides also explanation for the existence of the wall flow and based on this explanation special wall flow deflecting rings (WFDR) have been proposed[15]. These rings are regularly spaced along the column length and contact at the outer edge the column wall. The small widths of the WFDR's and relatively large spacing contribute to low installation costs which do not exceed 2% of the total column costs. Investigations[14] have shown that with a suitable spacing of the WFDR's the column wall appears to acquire the capability to reflect the trickling liquid. The research of absorption and desorption in three different systems in both the pilot-plant[16–18] and industrial scale[2] columns equipped with WFDR's has shown that the mass transfer coefficient in such column does not depend on the column diameter nor the height of the packed section.

In spite of the fact that columns with WFDR have already found its industrial application in various absorption and desorption processes, the problem of optimum spacing of the WFDR's for a given size has not been resolved. The aim of the work undertaken by the authors of this paper is to develop the method of calculation of the optimum spacing. This goal encompasses three following steps: *1*) Mathematical modelling of the liquid flow distribution in a packed layer with a single WFDR; *2*) Mathematical modelling of the liquid flow distribution in a column with a set of equally spaced WFDR's; *3*) Optimum spacing of the WFDR's in the column in dependence on the parameters of the process taking place in the column.

The present paper tackles the first of these problems.

THEORETICAL

Mathematical Model

For the distribution of the density of irrigation in a random packed layer Cihla and Schmidt[19] derived an equation similar to that governing the diffusion. In case of an axially symmetric flow this equation takes the following form

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

Cihla and Schmidt solved this equation for the case of a column with a wall perfectly reflecting the trickling liquid and a number of initial conditions[19,20].

Detailed theoretical and experimental studies[21–23] showed that in the real packed bed column a boundary condition that better characterizes the conditions of liquid distribution near the column wall is as follows

$$-\partial f(r, z)/\partial r = B[f(r, z) - CW]\,, \quad r = 1\,. \qquad (2)$$

This condition then helps us calculate satisfactorily the distribution of liquid including the wall flow effects.

The coefficient B in the last equation expresses the intensity of liquid exchange between the flow on the wall and that over the surface of the packing. The coefficient C characterizes the equilibrium distribution of liquid between the wall flow and the flow within the packing. The equilibrium conditions are reached theoretically on an infinite depth of the packing.

According to experimental studies[23] the coefficients B and C do not depend on the mean density of irrigation, the type of the initial distribution of liquid on the top of the packed layer, nor on the depth of the layer. The parameter B appears also independent of the ratio of the packing to column diameter and for Raschig rings assumes a value of 6·7.

The coefficient C depends on the above mentioned ratio of diameters and may be determined from the following correlation[24]

$$C = k\, d_k/d_p\,, \tag{3}$$

where the constant k equals 0·181 for Raschig rings.

The general form of the solution of Eq. (1) with the boundary condition (2) is following

$$f(r, z) = A_0 + \sum_n A_n J_0(q_n r) \exp\left(-q_n^2 z\right), \tag{4}$$

where q_n designate the roots of the characteristic equation in the form

$$\left(\frac{2C}{q_n} - \frac{q_n}{B}\right) J_1(q_n) + J_0(q_n) = 0\,. \tag{5}$$

The coefficient A_0 is a constant given as

$$A_0 = C/(1 + C)\,. \tag{6}$$

The coefficients A_n depend on the type of initial liquid distribution, *i.e.* the initial condition. The paper[25] presents solutions for various types of initial distribution of the density of irrigation on the top of the packed bed (disc, annulus, circle, central point source, *etc.*). The initial distribution in the presence of the WFDR located between the top of the bed and the distributor proper (Fig. 1) is mathematically defined in (7) and may be looked upon as being a combination of a disc distributor of radius r_1 and a circular distributor of the same radius

$$\begin{aligned} f(r, z) &= 1 \quad && z = 0\,; \quad 0 \leqq r < r_1 \\ f(r, z) &= \infty && z = 0\,; \quad r = r_1 \\ f(r, z) &= 0 && z = 0\,; \quad r_1 < r \leqq 1\,. \end{aligned} \tag{7}$$

Material balance mandates also the following constraint on the initial distribution

$$2\int_0^1 f(r, z)\, r\, \mathrm{d}r = 1\,, \quad z = 0\,. \tag{8}$$

The solution for a disc distributor of dimensionless radius r_1 takes the form

$$f_\mathrm{d}(r, z) = \frac{C}{1 + C} + \frac{1}{r_1} \sum_\mathrm{n} \frac{2((q_\mathrm{n}^2/B) - 2C)^2\, \mathrm{J}_1(q_\mathrm{n} r_1)\, \mathrm{J}_0(q_\mathrm{n} r) \exp(-q_\mathrm{n}^2 z)}{[((q_\mathrm{n}^2/B) - 2C)^2 + q_\mathrm{n}^2 + 4C]\, q_\mathrm{n} \mathrm{J}_0^2(q_\mathrm{n})}\,, \tag{9}$$

while for a circular distributor of the same radius we may write

$$f_\mathrm{c}(r, z) = \frac{C}{1 + C} + \sum_\mathrm{n} \frac{2((q_\mathrm{n}^2/B) - 2C)^2\, \mathrm{J}_0(q_\mathrm{n} r_1)\, \mathrm{J}_0(q_\mathrm{n} r) \exp(-q_\mathrm{n}^2 z)}{[((q_\mathrm{n}^2/B) - 2C)^2 + q_\mathrm{n}^2 + 4C]\, \mathrm{J}_0^2(q_\mathrm{n})}\,. \tag{10}$$

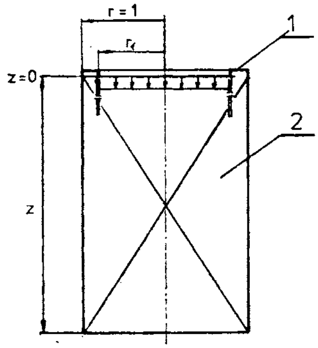


FIG. 1

Scheme of initial distribution of liquid. *1* Wall flow deflecting ring, *2* packing

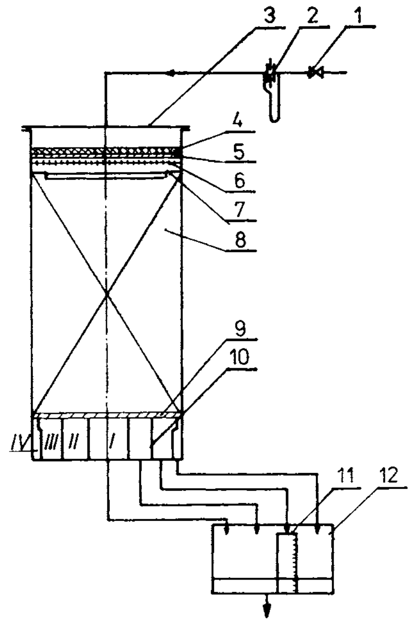


FIG. 2

Scheme of experimental set-up. *1* Valve, *2* rotameter, *3* column, *4* filter, *5* supporting mesh of the filter, *6* distributing tubes, *7* wall flow deflecting ring, *8* packing, *9* grid, *10* collecting device, *11* measuring cylinder, *12* tank

From the material balance (*8*) there follows that the disc distributor supplies r_1^2 fraction of the total volume flow rate, and correspondingly the circular distributor supplies $(1 - r_1^2)$ fraction of the total rate. The solution for the distribution in the presence of the WFDR thus may be constructed as

$$f(r, z) = f_d(r, z)\, r_1^2 + f_c(r, z)\,(1 - r_1^2)\,. \tag{11}$$

After substituting Eqs (*10*) and (*9*) into Eq. (*11*) and after some manipulation there results

$$f(r, z) = \frac{1}{1 + C} + \sum_n \left\{ \frac{((q_n^2/B) - 2C)^2\, J_0(q_n r) \exp(-q_n^2 z)}{[((q_n^2/B) - 2C)^2 + q_n^2 + 4C]\, J_0^2(q_n)} \cdot \left[\frac{2r_1\, J_1(q_n r_1)}{q_n} + (1 - r_1^2)\, J_0(q_n r_1) \right] \right\}. \tag{12}$$

The mean density of irrigation in an annular section of the column cross section, delimited by the radii R_1 and R_2 $(R_2 > R_1)$, can be obtained by integration with the appropriate weighting factor

$$\bar{f}_{12} = \frac{2}{R_2^2 - R_1^2} \int_{R_1}^{R_2} f(r, z)\, r\, \mathrm{d}r =$$

$$= \frac{C}{1 + C} + \frac{2}{R_2^2 - R_1^2} \sum_n \left\{ \frac{((q_n^2/B) - 2C)^2\, [R_2\, J_1(q_n R_2) - R_1\, J_1(q_n R_1)] \exp(-q_n^2 z)}{[((q_n^2/B) - 2C)^2 + q_n^2 + 4C]\, J_0^2(q_n)\, q_n} \cdot \left[\frac{2r_1\, J_1(q_n r_1)}{q_n} + (1 - r_1^2)\, J_0(q_n r_1) \right] \right\}. \tag{13}$$

The magnitude of the wall flow can be obtained from the overall balance on the

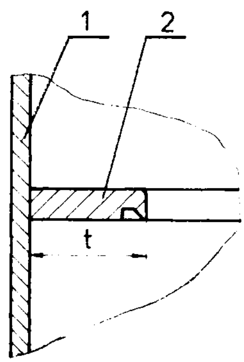


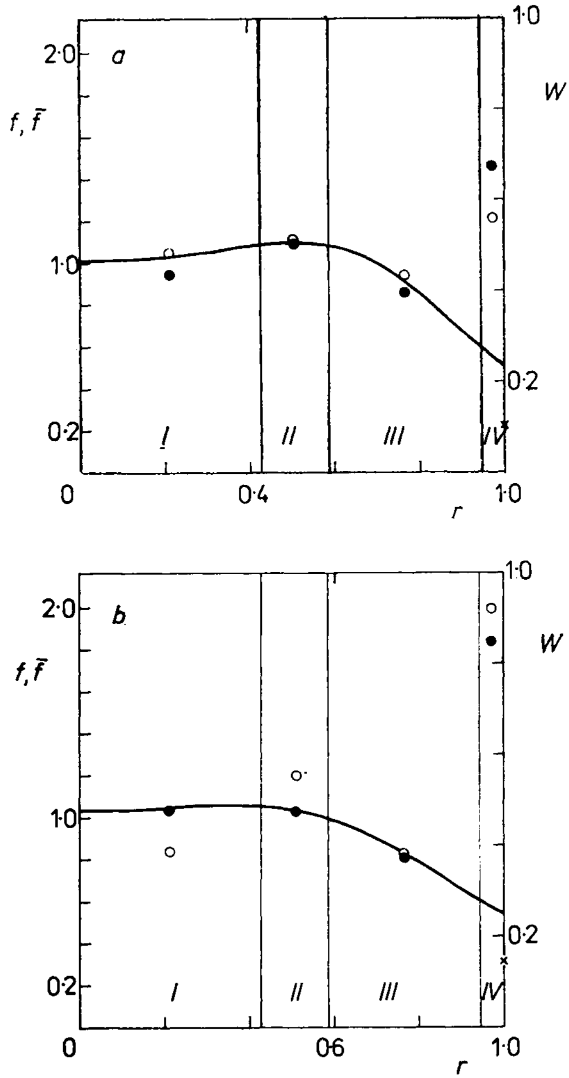
FIG. 3
Detail of construction of the wall flow deflecting ring. *1* Column wall, *2* wall flow deflecting ring

flowing liquid in the form

$$W = 1 - 2\int_0^1 f(r, z)\, r\, \mathrm{d}r =$$

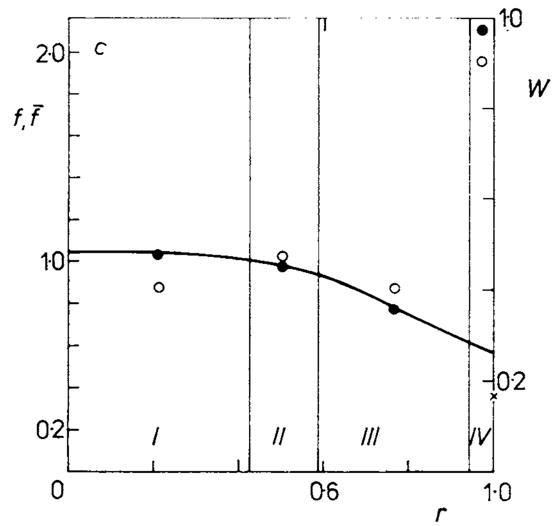
$$= \frac{1}{1 + C} - 2\sum_n \left\{ \frac{((q_n^2/B) - 2C)^2\, J_1(q_n) \exp(-q_n^2 z)}{[((q_n^2/B) - 2C)^2 + q_n^2 + 4C]\, J_0^2(q_n)\, q_n} \cdot \right.$$

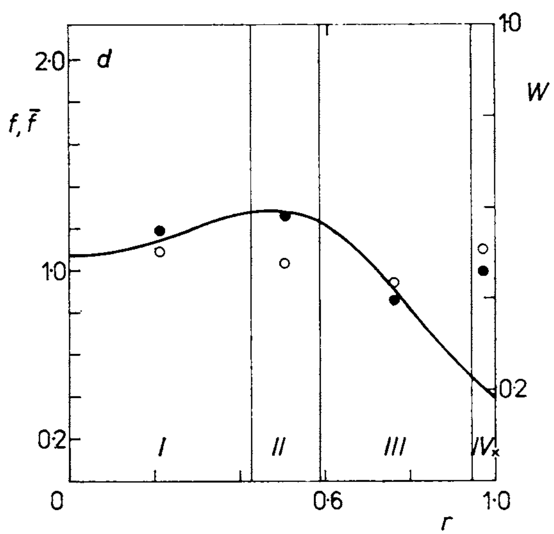
$$\left. \cdot \left[\frac{2r_1\, J_1(q_n r_1)}{q_n} + (1 - r_1^2) J_0(q_n r_1) \right] \right\} . \qquad (14)$$



EXPERIMENTAL

The experiments were carried out in a perspex glass column 188·6 mm in diameter (Fig. 2) with no gas flow. Water was supplied from a constant head tank equipped with an overflow weir (not shown in the figure) *via* a regulating valve *1*. After metering in a bank of rotameters *2* water proceeded to a ducaprene filter *4* and the experimental column *3*. After passing the supporting mesh *5* of the filter *4* water entered a distributor feeding the liquid into the column through 236 capillary tubes evenly distributed over the column cross section (8 448 tubes/m^2). Below the distributor there was a wall flow deflecting ring *7*, a layer of packing *8* made of ceramic





Raschig rings 25 × 25 × 3 mm. A packing supporting grid *9* was manufactured from a piece of expanded metal sheet. Immediately below the layer of packing there was a water collecting device *10* consisting of a set concentric tubes. In order to better define the area of the collecting sections the upper end of the collecting tubes was tapered. The radii of the water collecting tubes

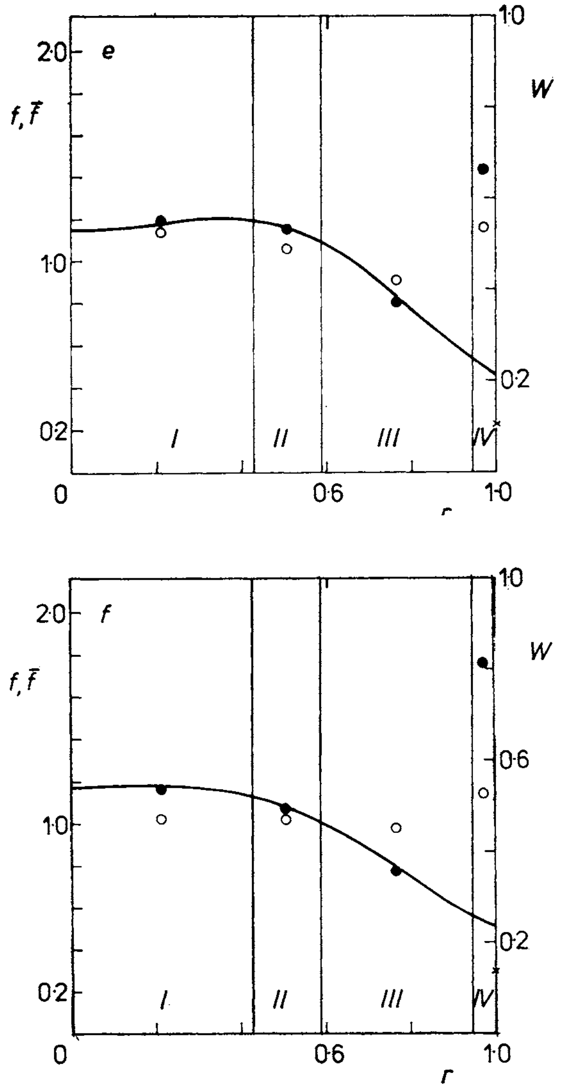


FIG. 4

Comparison of computed and experimental results. ● Computed mean density of irrigation, ○ experimental mean density of irrigation, × wall flow. Figures *a*, *b*, *c*, *d*, *e*, *f* correspond to experimental runs 1—6 in Table II (the flow rate through segment IV includes also the wall flow)

TABLE I
Dimensions of the water collecting cylinders

Designation of collecting segment		I	II	III	IV
Radius mm	internal	0	40·2	55·3	88·9
	external	40·2	55·3	88·9	94·3

TABLE II
Results of experiments

Experiment No	t	h	Segment No	f_E	f_T	%
1	20	100	I	0·95	1·05	−9·5
			II	1·10	1·09	0·9
			III	0·94	0·86	9·3
			IV	1·21	1·46	−17·1
2	20	150	I	0·83	1·05	−20·9
			II	1·20	1·03	16·5
			III	0·82	0·80	2·5
			IV	2·00	1·84	8·7
3	20	200	I	0·87	1·03	−15·5
			II	1·03	0·97	6·2
			III	0·88	0·77	14·2
			IV	1·95	2·10	−7·1
4	30	100	I	1·09	1·19	−8·4
			II	1·03	1·27	−18·9
			III	0·94	0·86	9·3
			IV	1·10	1·00	10·0
5	30	150	I	1·14	1·19	−4·2
			II	1·06	1·15	−7·8
			III	0·91	0·80	13·7
			IV	1·16	1·43	−18·8
6	30	200	I	1·02	1·16	−12·1
			II	1·02	1·07	−4·7
			III	0·97	0·77	26·0
			IV	1·14	1·76	−35·2

are summarized in Table I, the designation of the collecting segments being identical with that shown in Fig. 2.

From the collecting cylinders the water was supplied to a measuring bank to be metered. Preliminary experiments showed that the distributor operated with an average deviation of $\pm 5.6\%$ from the uniform flow. It was checked that the supporting grid *9* did not affect the results of measurement.

For a good function of the WFDR it is necessary that the deflected liquid does not return back on the lower surface of the ring facing the column bottom. In order to ensure this the rings were modified in the way shown in Fig. 3.

The experiments were carried out with WFDR's 20 and 30 mm wide and at different heights of the packed section (100, 150 and 200 mm). The density of irrigation was adjusted to $2 \cdot 10^{-3}$ $m^3 m^{-2} s^{-1}$. The deviation of the data of replica experiments amounted to less than 2%. The differences between repeated experiments after repacking the column, however, were substantially higher. With the aim to increase the accuracy each experimental profile was an average of six individual experimental runs between which the column was always repacked. The standard deviation of the mean obtained in this manner amounted to 11·7%.

RESULTS AND DISCUSSION

The results of experiments and theoretical calculations are presented in Table II. The same results are simultaneously presented in Figs $4a-f$ for each individual case (black points show the computed mean density of irrigation for each collecting segment; empty circles show the mean experimental density of irrigation). In addition the figures show also the computed distribution of the local density of irrigation as a function of the radial coordinate. The right hand side ordinate shows also the dimensionless magnitude of the wall flow, *W*. The calculations respected the fact that the collecting segment IV collected not only the liquid from the corresponding area of cross section but also the whole wall flow. In all calculations the coefficient of radial spreading of liquid, *D*, was taken equal 0·0027 m on the basis of the correlation published in ref.[26].

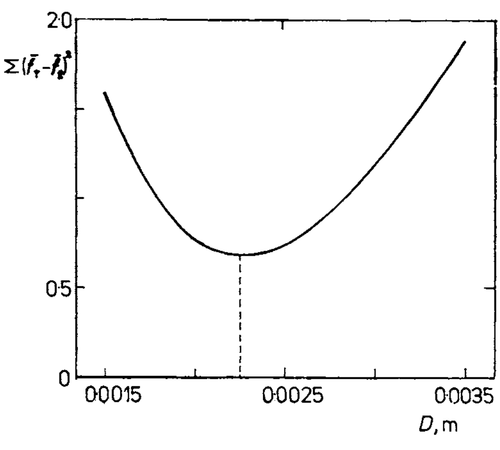


FIG. 5

Residual summ of square deviations as a function of the coefficient of radial spreading of liquid

As may be seen from Table II and Figs 4 the results of the calculation satisfactorily agree with the experimentally found data. It is noted though that the data on the coefficient of radial spreading of liquid in the literature considerably differ. In some cases by as much as a factor of two. For 25 mm Raschig rings, for instance, Tour and Lerman[27] recommended $D = 0{\cdot}0017$ m while Kabakov and Dilman[28] $D = 0{\cdot}0038$ m. The above used value D falls between these two extreme values. In view of this scatter of results we found it necessary to examine the agreement between the model and experiment in dependence on the adopted value of the coefficient of spreading of liquid. As a criterion we took the sum of square deviations between the model and experimental data. The results of this optimization are presented in Fig. 5. From this figure it is apparent that the residual sum of square deviations exhibits a clear minimum for $D = 0{\cdot}00225$ m, *i.e.* a value not far from that adopted above (0·0027 m).

The adequacy of the model has been tested with aid of the Fischer criterion in the form of the ratio of the residual sum of square deviations (S_0^2) and the variance of reproduced experiments (S_E^2)

$$F = S_0^2/S_E^2 . \tag{15}$$

In this test the effect has been also tested of the value of the coefficient of radial spreading of liquid, similarly as in Fig. 5. The results showed that at the 10% significance level[29] the model appears adequate on the interval $D = 0{\cdot}0017 - 0{\cdot}0029$ m.

LIST OF SYMBOLS

A_0, A_n	coefficients in Eq. (4)
B, C	dimensionless parameters of the boundary condition (2)
D	coefficient of radial spreading of liquid, m
d_k, d_p	column and packing diameter, m
$f = L/L_0$	dimensionless density of irrigation
$\bar{f}$	mean density of irrigation
F	Fischer criterion
J_0, J_1	Bessel function first kind zero and first order
L, L_0	local and mean density of irrigation, m s^{-1}
n	summation index
q_n	roots of characteristic equation (5)
R	column radius, m
r'	radial coordinate, m
$r = r'/R$	dimensionless radial coordinate
r_1	dimensionless internal radius of WFDR
S^2	variance
t	width of WFDR, m
W	dimensionless wall flow (fraction of total volume flow rate)
$Z = Dh/R^2$	dimensionless height of bed

$\delta = 100 (j_E - j_T)/j_T$ relative deviation of experimental and theoretical density of irrigation for a given collecting segment, %

Subscripts

T theoretical
E experimental

REFERENCES

1. Ramm V. M.: *Absorpcia gazov.* Khimia, Moscow 1976.
2. Kolev N.: *Thesis.* Bulgarian Academy of Sciences, Sofia 1980.
3. Dutkai E., Ruckenstein E.: Chem. Eng. Sci. *23*, 1365 (1968).
4. Porter K. E., Barnett V. D., Templeman J. J.: Trans. Inst. Chem. Eng. *46*, T 80 (1968).
5. Porter K. E., Jones M. C.: Trans. Inst. Chem. Eng. *41*, 240 (1963).
6. Zarzycki R.: Inzynieria Chemiczna *1*, 85 (1971).
7. Jameson G. J.: Trans. Inst. Chem. Eng. *44*, T 198 (1966).
8. Jameson G. J.: Trans. Inst. Chem. Eng. *45*, T 74 (1967).
9. Leenaerts R.: Chim. Ind. (Milan) *96*, 947 (1966).
10. Herskowitz M., Smith J. M.: AIChE J. *24*, 439 (1978).
11. Stürman O. H.: *Thesis.* Universität Hamburg, Hamburg 1936.
12. Kirschbaum E.: Chem.-Ing.-Tech. *28*, 10, 638 (1965).
13. Reichelt W.: *Strömung und Stoffaustausch in Füllkörperapparaten bei Gegenstrom einer flüssigen und einer gasförmigen Phase.* Verlag Chemie, Weinheim 1970.
14. Kolev N., Daraktschiev R., Markov L.: Verfahrenstechnik *13*, 3, 164 (1979).
15. Kolev N., Daraktschiev R.: Patent No 18018 from 5. 5. 1972.
16. Kolev N., Daraktschiev R., Kolev L.: Energetika *5*, 10, 15 (1973), (in Bulgarian).
17. Kolev N., Daraktchiev R., Kolev L.: Teploenergetika *8*, 91, (1975).
18. Kolev N.: Chem.-Ing.-Tech. *47*, 16, 685 (1975).
19. Cihla Z., Schmidt O.: This Journal *22*, 896 (1957).
20. Cihla Z., Schmidt O.: This Journal *23*, 569 (1958).
21. Kolář V., Staněk V.: This Journal *30*, 1054 (1965).
22. Staněk V., Kolář V.: This Journal *32*, 4207 (1967).
23. Staněk V., Kolář V.: This Journal *33*, 1062 (1968).
24. Staněk V., Kolář V.: This Journal *38*, 1012 (1973).
25. Staněk V., Kolář V.: This Journal *38*, 2865 (1973).
26. Onda K., Takeuchi H., Maeda T., Takeuchi N.: Chem. Eng. Sci. *28*, 1677 (1973).
27. Tour R. S., Lerman F.: Amer. Inst. Chem. Eng. *40*, 79 (1944).
28. Kabakov M. I., Dilman W. W.: Teor. Osn. Kchim. Tekhnol. *7*, 4, (1973).
29. Mitropolskii A. K.: *Teknika statisticheskikh vychislenii.* Khimia, Moscow 1961.

Translated by the author (V. S.).