THE RADIAL SPREAD AND THE NUMBER OF RIVULETS IN A TRICKLE BED*

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The coefficient of radial spread of liquid was determined from radial distribution of a tracer on 3 packings of spheres of different diameter and 5 packings of Raschig rings. To evaluate the data a generalized model was used accounting for possible non-uniformity of the flow of the liquid carrying the tracer, and a simplified model assuming constant density of wetting throughout the column. Although the coefficients of radial spread following from the two models do not differ appreciably the agreement between the experiment and the theoretical distribution given by the generalized model improves by 50—60%. The scatter of the experiment about the theoretical distribution of the tracer provided an estimate of the number of liquid rivulets trickling down the packing and their mutual mixing. The results suggest that under very low densities of wetting the number of rivulets is given by the geometry of the packing, *e.g.* by the number of elements of packing appearing sectioned in a horizontal cross section of the column. At a relatively low density of wetting mutual mixing of the rivulets occurs and intensifies with increasing flow rate of liquid.

As more realistic for description of liquid distribution in random packings appear the two-dimensional models which, in contrast to one-dimensional ones, account also for possible non-uniformities in the radial profile. This paper deals with the method of evaluating the coefficient of radial spread and the character of liquid distribution in the packing. The method using a tracer was chosen for experiments. To evaluate the data the well-known model assuming uniform flow of liquid was used as well as a generalized model accounting for possible non-uniformities of the flow of liquid carrying the tracer due to the gradual build-up of the wall flow.

THEORETICAL

A balance on the tracer carried by the liquid trickling freely down the packing in a cylindrical column may be written *e.g.* in the form

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$$\frac{\partial(fc)}{\partial z} = \frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial(fc)}{\partial r}\right), \tag{1}$$

if it is assumed that the coefficient of radial spread is a constant independent of the density of wetting.

Under a generally non-uniform distribution of the density of wetting Eq. (*1*) must be put *e.g.* in the form

$$Df\left[\frac{\partial^2 c}{\partial r^2} + \frac{1}{r}\frac{\partial c}{\partial r}\right] = f\frac{\partial c}{\partial z} - 2D\frac{\partial c}{\partial r}\frac{\partial f}{\partial r}, \tag{2}$$

where for the distribution of f one can write from a balance on liquid the following equation

$$D\left[\frac{\partial^2 f}{\partial r^2} + \frac{1}{r}\frac{\partial f}{\partial r}\right] = \frac{\partial f}{\partial z}. \tag{3}$$

Thus it is assumed that the mechanism of the spread of the carrier liquid over the packing is the same as that of the spread of the tracer carried by the liquid trickling down the packing. Hence the coefficients in Eqs (*2*) and (*3*) are identical. In a particular case of the uniform flow of liquid over the packing Eq. (*2*) simplifies to

$$D\left[\frac{\partial^2 c}{\partial r^2} + \frac{1}{r}\frac{\partial c}{\partial r}\right] = \frac{\partial c}{\partial z}. \tag{2a}$$

By solving Eq. (*3*) for a uniformly wetted column one obtains the following expression[1]

$$f^* = \frac{C}{1 + C} + \sum_{n=1}^{\infty} \frac{2[(q_n^2/B) - 2C]\, J_0(q_n r^*) \exp\left[-q_n^2 \mathrm{To}\right]}{\{[(q_n^2/B) - 2C]^2 + q_n^2 + 4C\}\, J_0(q_n)}, \tag{4a}$$

where B and C are dimensionless parameters of the following boundary condition

$$-\frac{\partial f^*}{\partial r^*} = B(f^* - CW^*), \quad r^* = 1 \tag{4b}$$

and the eigenvalues q_n satisfy the equation

$$[(2C/q_n) - (q_n/B)]\, J_1(q_n) + J_0(q_n) = 0. \tag{4c}$$

Solutions to Eq. (*2a*) for various initial conditions may be found in standard textbooks[2]. Assuming that the liquid entering the packing at its top in the region $0 \leqq r^* < r_1^*$ carries the tracer, and, further, that the tracer cannot escape from the packing, *i.e.*

$$0 \leqq r^* < r_1^* \,, \quad z = 0 \,, \quad c^* = 1 \,; \quad r_1^* < r^* \leqq 1 \,, \quad z = 0 \,, \quad c^* = 0 \,;$$
$$r^* = 1 \,, \quad r^* = 0 \,, \quad (\partial c^* / \partial r) = 0 \qquad (5a)-(5c)$$

the solution may be written as

$$c^* = (r_1^*)^2 + 2r_1^* \sum_{n=1}^{\infty} \frac{J_1(q_n r_1^*)\, J_0(q_n r^*) \exp\left[-q_n^2 \,\mathrm{To}\right]}{q_n J_0^2(q_n)} \,, \qquad (6)$$

where for q_n we have that $J_1(q_n) = 0$.

The last model served to evaluate the data in all papers dealing with the distribution of the tracer in random packings, *e.g.* ref.[3]. At the same time, however, the literature indicates[4-8] that even a perfectly uniform wetting of the column top does not ensure the uniformity of the flow in all column cross sections. In such case it is more proper to use the more general model formulated in Eq. (*2*) and to derive the necessary expressions containing the density of wetting of the carrier liquid from Eq. (*4a*).

EXPERIMENTAL

The distribution of the tracer over the packing. The packing at its top was uniformly wetted by liquid "tagged" by the tracer within the radius $r_1 = 1/2$. The packing rested on a set of concentric annuli directing the liquid into separate collecting vessels. Having reached the steady state the liquid in individual collecting vessels was sampled and analyzed and the results compared with the predicted distribution of the tracer according to the chosen model.

Apparatus. The glass column was 291 mm in inner diameter. The packing was supported by 12 concentric annuli about 10 mm wide. The set of annuli was further equipped with a wall flow separating device. The distributor was a brass cylindrical vessel with its outer diameter equalling the inner diameter of the column equipped with 2 mm hollow rivets in the bottom. The rivets were arranged in a square pitch at the density 1 rivet per square centimeter. The total number of rivets was 664. There were about 7 mm long nylon loops mounted in the opening of each rivet facilitating the dripping of liquid at low discharge velocities[4,5]. The space above the bottom of the distributor was divided into two mutually isolated chambers each with its own independent feed of liquid. The inner of the chambers was of circular cross section of the diameter equalling one half of the column diameter, *i.e.* the area of cross section equalling 1/4 of the column cross section. This chamber was supplied with water solution of the tracer, the outer chamber was fed with tap water at 25°C. The packings used were glass spheres 10, 15 and 20 mm in diameter and Raschig rings 8, 10, 15, 20 and 25 mm in diameter. The tracer liquid was aqueous solution of potassium chloride at concentration of 1 g/litre. The liquids were fed into the chambers of the distributor in the ratio of the flow rates 1 : 3 in order to keep the density of wetting on the top uniform. The correct ratio of the flow rates was checked from the balance on the tracer on the exit of the column.

The experimental routine. The measurements were carried out on layers of packing 200, 300, 400 and 500 mm high. The routine was started by flooding the packing with water and setting then the flow rates of both liquids (1 : 3) at the values corresponding to the preselected mean density of wetting. Having reached the steady state the liquid draining from individual openings and the wall flow separator was mechanically diverted to the collecting vessels to collect samples of about 0·5—2 litres. About 50 ml samples were then taken from each collecting vessel and the set of 13 samples was supplemented with a sample of the inlet tracer solution as well as the tap water from the storage tanks. The analysis of the sample was carried out by conductometry.

Data processing. The results of the analysis were processed to give the dimensionless concentration of the tracer in twelve collecting annuli and in the wall flow, c^* (the real dimensional concentration scaled by the initial concentration of the tracer solution c_i). The mean radii of the collecting annuli, r^*_m, were computed from the outer and the inner radius r^*_0, r^*_i from the relation[9]

$$r^*_m = (2/3)\,[r^*_0 + r^{*2}_i/(r^*_0 + r^*_i)]\,. \tag{7}$$

The experimental profiles of the dimensionless concentration were then compared with the values computed from Eq. (*6*) for various values of the dimensionless height of the packing, To, observing simultaneously the residual sum of square deviations with the aim to find To corresponding to the minimum of the residual sum. The computational routine was based on taking a sufficiently wide interval of To encompassing the minimum and subsequent narrowing the interval. The computation was terminated when the width of the interval amounted to less than 3% of its average value taken for the result. The resulting To then served to compute the coefficient of radial spread D. As an advantage of this approach, in contrast *e.g.* to the method of moments, is that each experimental point of the concentration profile is assigned the same statistical weight[10].

As has been pointed in the theoretical part even perfect uniformity of wetting of the column top does not ensure the uniformity of the flow in all cross sections as a consequence of the formation of the wall flow. Only those packings characterized by an infinite value of the parameter C (see Eq. (*4b*)) are perfectly free of the wall effect. In order that the wall flow may achieve a substantial degree (*e.g.* 20% of the total flow rate of liquid) the value of C would have to drop to $C =$ $= 4$. In case of Raschig rings, which are more apt to wall flow formation, this value will be reached if the column-to-packing ratio drops to about[5] $(d_c/d_p) = 11$. For even lower values of this ratio the magnitude of the wall flow will progressively increase. Analogous critical value for a packing of spheres is approximately one half of the former[5]. From this reasoning it follows that evaluation of the results according to the model formulated in Eq. (*2*) could provide results substantially different from those of the model in Eq. (*6*) only in case of 25 mm Raschig rings.

For numerical purposes Eq. (*2*) was rendered dimensionless as follows

$$\frac{\partial^2 c^*}{\partial r^2} + \frac{1}{r^*}\frac{\partial c^*}{\partial r} = \frac{\partial c^*}{\partial \mathrm{To}} - 2\,\frac{\partial c^*}{\partial r^*}\,\frac{\partial \ln f^*}{\partial r^*}\,. \tag{8}$$

The initial condition is identical to that in Eq. (*5a*) where $r^*_1 = 1/2$. For simplicity the boundary condition is formulated also identically as that in Eq. (*5c*) although it must be realized that this condition for the given model provides only for the convective transport of the tracer into the wall flow, *i.e.* together with the carrier liquid, and not by diffusion. Thus the condition (*5c*) is acceptable only in the initial stage of the distribution when the concentration gradient as well as the concentration of the tracer near the wall are both small. Retaining the same boundary condition also in subsequent stages of the distribution would mean that after formation of the equilibrium wall flow (which in case of the uniform initial wetting may take place quite rapidly no additional tracer could be transferred into the wall flow despite of possibly different concentrations in the liquid near the wall and in the wall flow. This situation is of course at odds with reality. However, to formulate a more general condition would require an independent experimental study beyond the scope of this work. Besides, the experimentally found concentrations in the wall flow were in all cases small which makes the condition (*5c*) satisfactory for the purposes of this work.

Eq. (*8*) was solved numerically using an implicit technique of solution. For reasons following from considerations about the magnitude of the wall flow and for the economy of the computation (the search of the optimum To for a single concentration profile took about three minutes on the Tesla 200 computer) the more general model was applied only in case of 25 mm Raschig rings. For the necessary parameters of the boundary condition, Eq. (*4b*), we took[5] $B = 7{\cdot}0$ and $C = 3{\cdot}12$. For each numerical step in direction of the dimensionless height To the program evaluated the residual sum of square deviations of the experimental profile with the strategy aimed at finding the optimum To.

RESULTS AND DISCUSSION

The coefficient of radial spread. The coefficients of radial spread were evaluated from Eq. (*6*) for all packings. Both models were used in case of 25 mm Raschig rings, *i.e.* also the numerical solution of Eq. (*8*). From comparison of the results according to both models it follows that the differences in D are small, usually only a few percent. However, substantial improvement in favour of the more complex model accounting for the non–uniformities of the flow of the carrier liquid was achieved in the residual sum of square deviations. The improvement of the fit of the experimental and the predicted distribution increases with increasing height of the packing, because the deviations from the uniform flow also grow with the packing height. For a 400 mm high layer of packing the decrease of the residual sum of square deviations is already very marked and in most cases exceeds 50% of the residual sum of the model assuming the uniform flow. From these observations it follows that the model represented by Eq. (*8*) describes substantially better the real situation on the packing despite of the fact that the differences in D domain are not conspicuous. The situation is illustrated in Fig. 1 plotting the experimental points of the tracer distribution for an experiment on 400 mm layer of 25 mm Raschig rings and the mean density of wetting $f_0 = 0{\cdot}008$ m/s. The curve *2* represents the solutions of Eq. (*8*) for the numerically found optimum value $D = 2{\cdot}182$ mm (parameters B and C taken respectively[5] equal 7·0 and 3·12). The residual sum of square deviations amounted to $6{\cdot}1495 \times 10^{-3}$. The curve *1* represents the solution (*6*) for the optimum value $D = 2{\cdot}188$ mm and the residual sum in this case equalled $1{\cdot}3646 \cdot 10^{-2}$.

Resulting values of D for all packings are plotted in Figs 2–4 as functions of the mean density of wetting. Full line in each figure passes through average D computed from results on various heights of packing. In computing the average individual values of D were weighed by the inverse of the residual sum of square deviations from the model distribution. From the figures it is apparent that D may be well regarded as independent of the density of wetting. Certain correlation appearing in some cases at the lowest mean densities of wetting is apparently caused by poorly reproducible peculiarities of distribution under low liquid flow rates. Increased scatter of the results of D on individual heights of the packing is typical for this region. Increased scatter display also packings of large characteristic dimensions (Fig. 4).

In view of the established independence of D on the mean density of wetting each packing diameter was assigned its characteristic average value of D. In the calculation of the average D the individual values were again weighed by the inverse of the residual sum of square deviations. The found averages are shown in Fig. 5. In contrast to the conclusion of the previous papers[9,11] D cannot be regarded for a given type of the packing as independent of the size of the packing element. The values of D from this work agree well with the universal values for spheres (1·383 mm) and Raschig rings (2·123 mm) reported earlier[11] in case of 15 and 20 mm spheres and 20

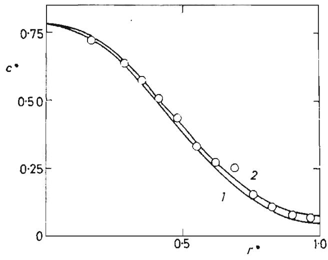

FIG. 1

The Profile of Tracer Concentration on a Packing of Raschig Rings $d_p = 25$ mm, $z = 400$ mm, $f_0 = 0{\cdot}008$ m/s

1 Computed from Eq. (*6*), *2* computed from Eqs (*4a*) and (*8*) for $B = 7$ and $C = 3{\cdot}12$.

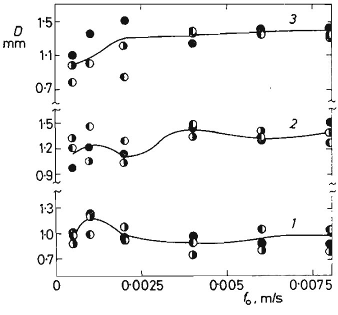

FIG. 2

The Coefficient of Radial Spread as a Function of the Mean Density of Wetting for Spherical Packing

1 $d_p = 10$ mm; *2* $d_p = 15$ mm; *3* $d_p = 20$ mm; ◐ $z = 300$ mm, ◑ $z = 400$ mm, ● $z = 500$ mm.

and 25 mm Raschig rings. The deviations toward lower values occur for smaller packings which were measured earlier[11]. These differences may be caused by large gradients of the density of wetting existing in the packing under measurements based on the spread of liquid[11], not the tracer, and thus by certain differences in mechanisms of distribution of the liquid and the tracer. In such a case, of course, the coefficients D appearing in Eqs (*2a*) and (*3*) would be different.

As it is seen from Fig. 5 the dependence of D on the characteristic dimension of the packing is not simple and no attempt was made to correlate D and d_p in view of the limited number of data. It is noted, however, that the results with Raschig rings would obey fairly well the correlation $D = 0{\cdot}169 \times d_p^{0.5}$ (both quantities in centimeters) published by Onda and coworkers.[12] This correlation was evaluated from tracer experiments of several authors on Raschig rings and Berl saddles.

The estimate of the number of liquid rivulets trickling down the packing. Both the above models describe the distribution of the tracer as well as the trickling liquid by means of the continuous functions c and f. In reality the liquid trickles down under low densities of wetting in the form of rivulets forming with increasing density of wetting a more or less continuous film of liquid on the surface of the packing. The continuous functions c and f are thus a certain abstraction of the reality and

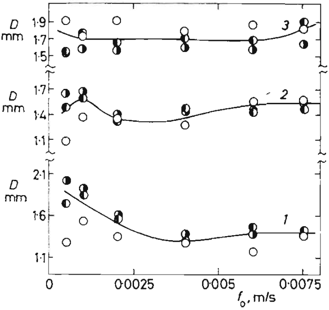

FIG. 3

The Coefficient of Radial Spread as a Function of the Mean Density of Wetting for Raschig Rings

1 $d_p = 8$ mm; *2* $d_p = 10$ mm; *3* $d_p = 15$ mm, ○ $z = 200$ mm, ◐ $z = 300$ mm, ◑ $z = 400$ mm.

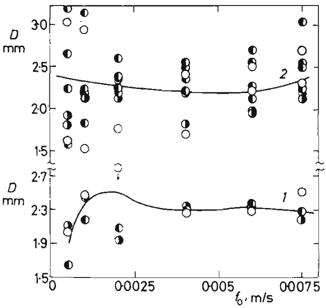

FIG. 4

The Coefficient of Radial Spread as a Function of the Mean Density of Wetting for Raschig Rings

1 $d_p = 20$ mm; *2* $d_p = 25$ mm; ○ $z = 200$ mm, ◐ $z = 300$ mm, ◑ $z = 400$ mm.

changing to a discretized model would require the knowledge of the intensity of individual rivulets. The fit of the predicted and the true conditions on the packing will necessarily be the closer the greater the number of liquid rivulets.

Let us suppose now that the liquid trickles down the packing in the form of N rivulets uniformly distributed over the column cross section. The rivulets do not interfere and mix mutually (coalescence and spliting) and their number remains constant along the height of the column. Let us denote further by P_i the fractional area of the i-th annulus collecting the liquid at the bottom of the packing. Subscript i varies between 1 and k, where k is the total number of the annuli and $\sum_{i=1}^{k} P_i = 1$. Thus in accord with our experimental arrangement $N/4$ rivulets at the top are KCl-traced and the rest are free of the tracer. The total number of rivulets, both the KCl-traced and the tracer-free ones, draining at the bottom into the i-th annulus equals NP_i. On taking the dimensionless concentration c^* so as to make the inlet concentration of the tracer equal unity, (see Eq. (5a), (5b)), the number of tracer containing rivulets draining through the same annulus equals c^*NP_i. Denoting the dimensionless concentration given by the theoretical model as c_t^* and the experimentally

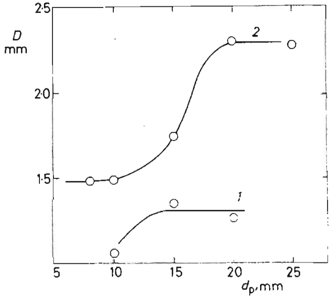

FIG. 5

Characteristic Values of the Coefficient of Radial Spread as a Function of d_p

1 Spheres; 2 Raschig rings.

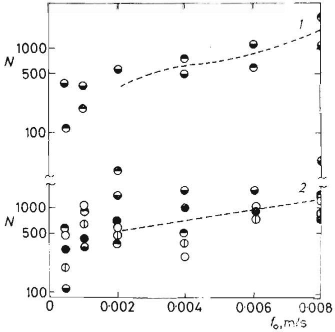

FIG. 6

The Number of Rivulets Trickling in the Packing of Raschig Rings as a Function of the Mean Density of Wetting

1 Spheres; 2 Raschig rings, ○ $d_p = 8$ mm; ⦶ $d_p = 10$ mm; ◒ $d_p = 15$ mm; ◓ $d_p = 20$ mm; ● $d_p = 25$ mm.

found concentration as c_e^* the expression for the χ^2 (chi-square) quantity testing the goodness-of-fit of the model frequency distribution may written as

$$\chi^2 = N \sum_{i=1}^{k} P_i (c_e^* - c_t^*)^2 / c_t^* \,. \tag{9}$$

Exact fit of the theoretical frequency to experimental measurements would correspond to $\chi^2 = 0$. Unlike the majority of practical utilization of the chi-square goodness-of-fit test the quantity N is unknown. The expression in Eq. (*9*) may then be used in reverse for an estimate of N provided that $c_t^* N$ represents a verified model of the frequency distribution of the tracer rivulets. On substituting the mean value of the quantity χ^2, following from the frequency distribution $F(\chi^2)$ on the left hand side of Eq. (*9*), the total number of rivulets may be expressed as

$$N = \nu / \sum_{i=1}^{k} P_i (c_e^* - c_t^*)^2 / c_t^* \,. \tag{10}$$

Similarly one can determine the upper and the lower bounds of the interval estimate for N. Since the number of collecting annuli and hence the number of degrees of freedom is relatively low the results of N must be expected to be only rough estimates. The principle of this method in a different arrangement was proposed by Porter, Barnett and Templeman[3].

The estimates of N were carried out simultaneously with the evaluation of the parameter To leading to the optimum value of D. Since the differences in the number of rivulets N found for a given packing and mean density of wetting on various

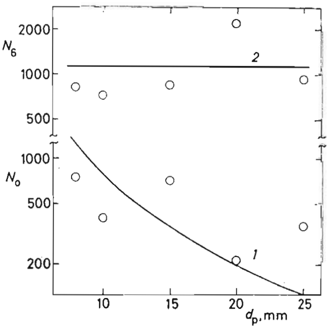

FIG. 7

N_0 and N_6 as a Function of d_p

1 Computed from Eq. (*11*) for $\varepsilon = 0{\cdot}4$ and $d_c = 291$ mm, *2* corresponding to constant $N_6 = 1114$.

heights of the layer were found insignificant, which is in agreement with the assumption of constant N along the column height, the results on individual heights of the layer were averaged. The averages are plotted in Fig. 6 as a function of the mean density of wetting. The course of these plots is in all cases analogous. The results with 10 mm spheres were excessively affected by systematic error which was not discovered during measurements and could not be used for evaluation. The relation between the number of trickling rivulets and the characteristic dimension d_p could thus be studied only on the packing of Raschig rings. As a first step the limiting value of the number of rivulets at zero density of wetting N_0 was estimated. Owing to the scatter of the data extrapolation of N_0 was replaced by taking the average N found at the two lowest mean densities of wetting (0·0005 and 0·001 m/s). In addition, we estimated the typical number of liquid rivulets, N_6, at the mean density of wetting equal 0·006 m/s. The estimate again was made by taking the average value of the number of rivulets at three largest mean densities of wetting (0·004, 0·006 and 0·008 m/s).

Both N_0 and N_6 are plotted in Fig. 7 for Raschig rings as functions of d_p. The correlation coefficient between N_0 and d_p was found equal −0·613, which is a value just above the limit of significance for the given number of degrees of freedom. Curve *1* in Fig. 7 follows the function

$$N_p = 3/2(1 - \varepsilon)\,(d_c/d_p)^2\,, \tag{11}$$

where N_p is the number of spherical particles sectioned by a horizontal cut through the column[13]. In view of the limited number of experimental results it can be tentatively accepted that the points N_0 approximately follow the curve *1* and hence that the number of liquid rivulets (or their paths) in the packing under low densities of wetting is dictated by the number of the elements of the packing sectioned in a horizontal column cross section, *i.e.* by the geometry of the packing.

In contrast, the correlation coefficient between N_6 and d_p was found equal 0·427 which is definitely an insignificant value. The average number of N_6 for Raschig rings equals 1114 and it is shown in Fig. 7 by horizontal straight line 2.

As the next step we examined the relation between the number of the rivulets and the mean density of wetting f_0. The correlation coefficient again for Raschig rings only is high and equal 0·975. Individual values of N for various d_p and packing heights for this purpose were averaged. With high probability it may be therefore stated that the number of liquid rivulets in the packing increases with the mean density of wetting, but it must be born in mind that the considerations leading to Eq. (*10*) for N included the assumption of mutual non-interference of the rivulets. However, coalescence, spliting and mingling of the rivulets can plaussibly take place either by direct contact of individual rivulets or be mediated by the static hold-up which is known to have a limited exchange of mass with the bulk of liquid[14,15].

Since mutual intermixing of the rivulets blurs the distinction between the tracer-containing the and tracer-free rivulets, even if the total number of the rivulets may remain unchanged, it causes the fit of the model and the experimental frequency distribution of the tracer rivulets to improve and hereby an apparent increase of N following from Eq. (*10*).

As has been mentioned the liquid distributor was designed so as to bring the liquid onto the packing through 664 hollow rivets. At low discharge rates the rivets only drip and visual observation showed the average volume of the droplet to be independent of the flow rate and equal 0·06 cm^3. With increasing flow rate the frequency of the droplets increases up to about $f_0 = 0{\cdot}004$ m/s when the rivets discharge continuous jets of liquid. Thus it is seen that the initial number if rivulets brought onto the packing is constant (equal 664) and only the frequency of dripping changes with increasing liquid flow rate. At higher densities of wetting, however, the calculated number of liquid rivulets considerably exceeds 664 (see Fig. 6). Since no additional splitting of the rivulets reaching the packing was observed the increase of N must have been caused by mutual intermixing of the rivulets which violated the basic prerequisite of applicability of Eq. (*10*). From the correlation between N and f_0 for Raschig rings it was found that N reaches 664 at f_0 equal approximately 0·003 m/s, which is a relatively low value. It may be thus concluded that under low densities of wetting the number of liquid rivulets is governed by the geometry of the packing and increasing flow rate of liquid causes soon mutual mixing of the rivulets. Considering the established independence of the apparent number of the rivulets at higher densities of wetting on d_p the character of the rivulet mixing in the packing may be also regarded as independent of the characteristic size of the packing element. For low densities of wetting when N reflects the true number of the rivulets in the packing one can thus evaluate the average intensity of an individual rivulet. From our data we get *e.g.* for 10 mm Raschig rings at $f_0 = 0{\cdot}002$ m/s about 0·27 cm^3 per second and rivulet.

LIST OF SYMBOLS

B, C	dimensionless parameter of boundary condition
c, $c^* = c/c_i$	dimensional and dimensionless tracer concentration
c_i	inlet tracer concentration
c_e^*, c_t^*	experimental and theoretical value of dimensionless concentration
D	coefficient of radial spread of liquid, (L)
d_c	column diameter, (L)
d_p	characteristic size of packing, (L)
$F(\chi^2) = \chi^{\nu-2} \exp(-1/2\chi^2)/(2^{\nu/2}(\nu/2 - 1)!)$	approximate frequency distribution function of χ^2 for $\nu > 5$
f, $f^* = f/f_0$	dimensional (LT^{-1}), dimensionless density of wetting
f_0	mean density of wetting, (LT^{-1})
i	summation index

J, J_1	Bessel function of the first kind, zero and first order
k	number of collecting annuli
N	number of liquid rivulets trickling in the packing
N_0, N_6	values of N at very low density of wetting and at $f_0 = 0{\cdot}006$ m/s respectively
N_p	number of spherical particles sectioned by an arbitrary horizontal cut through the column
n	summation index
P_i	dimensionless area of the i-th collecting annulus as fraction of column cross section
q_n	n-th eigenvalue
R	column radius, (L)
$r, r^* = r/R$	dimensional (L), dimensionless radius
r_1^*	dimensionless radius of the tracer distributing disc as a fraction of column radius
r_0^*, r_i^*, r_m^*	outer, inner and mean dimensionless radii of collecting annulus as fractions of column radius
$\mathrm{To} = Dz/R^2$	dimensionless height of packing
$u_{\mathrm{observed}}, u_{\mathrm{theoretical}}$	frequencies of a statistical quantity
$W, W^* = W/(R^2 f_0)$	dimensional ($\mathrm{L^3\,T^{-1}}$), dimensionless wall flow
z	coordinate of height
χ	packing porosity
ε	number of degrees of freedom
$\nu^2 = \sum(u_{\mathrm{observed}} - u_{\mathrm{theoretical}})^2/u_{\mathrm{theoretical}}$	chi-square quantity

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