DISTRIBUTION OF LIQUID OVER A RANDOM PACKING. VII.*

THE DEPENDENCE OF DISTRIBUTION PARAMETERS ON THE COLUMN AND PACKING DIAMETER

V. STANĚK and V. KOLÁŘ

Institute of Chemical Process Fundamentals,
Czechoslovak Academy of Sciences, Prague - Suchdol

Received February 23rd, 1972

The dependence of the parameters appearing in the boundary condition (*2*) on d_k and d_p was investigated experimentally using a glass column 291 mm diameter and four packings. In the correlation $C = k(d_k/d_p)$ proposed k equals 0·365 for Raschig rings and 0·181 for spheres. A correlation for packings of general shape was proposed. The latter, however, needs further experimental verification. The parameter B may be regarded within experimental error as independent of the size of packing. Its value was found equal 6·7 and 7·0 for spheres and Raschig rings respectively.

In an earlier paper of this series[1] solutions to the so called "diffusion" equation in cylindrical coordinates as

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

have been presented for our boundary condition in dimensionless form as:

$$-\frac{\partial f}{\partial r} = \mathrm{B}(f - \mathrm{C}W)\,, \quad r = 1\,. \qquad (2)$$

These solutions describe distributions of the density of wetting at two types of wetting of the top of packing: For the uniform initial wetting:

$$f^{\mathrm{u}} = \frac{\mathrm{C}}{1 + \mathrm{C}} + \sum_{n=1}^{\infty} \frac{2[(q_n^2/\mathrm{B}) - 2]\,\mathrm{J}_0(q_n r)\exp\left[-q_n^2 z\right]}{\{(q_n^2/\mathrm{B} - 2\mathrm{C})^2 + q_n^2 + 4\mathrm{C}\}\,\mathrm{J}_0(q_n)} \qquad (3)$$

and for the case that all liquid is initially introduced onto the wall (wall initial wetting):

$$f^{\mathrm{w}} = \frac{\mathrm{C}}{1 + \mathrm{C}} - \mathrm{C}\sum_{n=1}^{\infty} \frac{2[(q_n^2/\mathrm{B}) - 2\mathrm{C}]\,\mathrm{J}_0(q_n r)\exp\left(-q_n^2 z\right]}{\{(q_n^2/\mathrm{B}) - 2\mathrm{C})^2 + q_n^2 + 4\mathrm{C}\}\,\mathrm{J}_0(q_n)}\,, \qquad (4)$$

* Part VI: This Journal *33*, 3235 (1968).

where q_n are the roots of the characteristic equation:

$$[(2C/q_n) - (q_n/B)] J_1(q_n) + J_0(q_n) = 0 . \qquad (5)$$

The boundary condition (2) has been verified experimentally[2,3] and the dimensionless parameters B, C evaluated from experiments in a perspex column 110 mm diameter packed with glass spheres 10 mm diameter. Parameter B is a criterion of the ratio of resistance to transport of liquid within the packing and that between the packing and the wall of the column. Finite values of this criterion suggest that the resistance to transfer within the packing is not sufficiently large and thus the density of wetting near the wall is not generally in equilibrium with the wall flow. Parameter C is a criterion determining the equilibrium distribution of the total flow between the packing and the wall under steady state ($h = \infty$). The aim of this study was to find relations between these parameters and the diameter of column and packing, particularly in large scale equipment. The scale-up of the apparatus, however, was accompanied by certain difficulties in evaluation of the distribution parameters necessitating the use of new methods.

THEORETICAL

EVALUATION OF PARAMETER C

The simplest method at hand for evaluating C follows from the equilibrium distribution of the density of wetting under steady state. This distribution equals simply $f(z = \infty) = C/(1 + C)$ regardless of the type of initial wetting. This method was used in an earlier work[2,4] as well as in papers of other authors[5-7,8]. Its principal drawback is that in columns of larger diameter the height necessary to reach the steady state may be rather high and increases with the square of the column diameter. This is dictated by the dimensionless parameter To, identical for $z' = h$ with the dimensionless height of packing. On taking To = 0·2, D = 1·5 mm and d_k = 300 mm, then the necessary height of layer reaches 3 m. Yet, To = 0·2 is sufficient only if the initial wetting does not deviate drasticly from the equilibrium distribution. For this reason alternative methods of evaluation of C were needed. One possibility rests in the fact that the distribution under uniform and wall initial wettings (Eqs (3) and (4)) is of the following type:

$$f^u = C/(1 + C) + g(r, z) , \quad f^w = C/(1 + C) - C\, g(r, z) . \qquad (6), (7)$$

The function $g(r, z)$ is identical with the sum on the right hand side of Eqs (3) and (4). This function can be eliminated by a simple algebraic operation to obtain an expression for C:

$$C = f^w/(1 - f^u) . \qquad (8)$$

Since the integral and differential properties of distribution retain generally the same form, one can write:

$$C = M^w(r_1, r_2)/(r_2^2 - r_1^2 - M^u(r_1, r_2)) \quad (9)$$

and

$$C = -(\partial f^w/\partial r)/(\partial f^u/\partial r) \,. \quad (10)$$

The quantity $M^w(r_1, r_2)$ is defined as:

$$M^w(r_1, r_2) = 2\int_{r_2}^{r_1} r f^w \, dr \quad (11)$$

and the definition of $M^u(r_1, r_2)$ is analogous. The suitability of individual expressions for C follows from considerations regarding the accuracy of the quantities appearing in Eqs (*9*)–(*11*). It can be concluded immediately that Eq. (*10*) will be least suitable since it is known that differential characteristics evaluated from experimental curves are not very accurate. A relatively high accuracy can be achieved by numerical integration as would be necessary for Eq. (*11*). If, however, the radii r_1, r_2 are selected identical with the radii of the collecting cylindres used for experiments, the quantities $M^w(r_i, r_e)$ and $M^u(r_i, r_e)$ are directly measurable.

Let us note what are the preconditions of experiments designed for evaluation of C from one of Eqs (*8*)–(*11*). The requirement of constant function $g(r, z)$ calls for experiments on the same height of packing, preferably without repacking. (It is known that statistical variation of the distribution parameters due to repacking, particularly that of D, is considerable[4,9]). Designating the error of $M^w(r_1, r_2)$ and $M^u(r_1, r_2)$ by ΔM, the error of C is then:

$$\Delta C/\Delta M \approx dC/dM = C[(1/M^w(r_1, r_2)) + 1/(r_2^2 - r_1^2 - M^u(r_1, r_2))] \,. \quad (12)$$

Clearly, higher layers of packing are more suitable because for small layers the denominator of the second term in the bracket approaches zero. For higher layers the function $g(r, z)$ vanishes and only one experiment is needed in the limit $z \to \infty$. In contrast, low layers differ only slightly from initial distribution and thus carry little information about C. The accuracy of the method further decreases for columns with a small wall effect ($C \to \infty$). The adequacy of the model of liquid distribution cannot be of course judged from these results because still other models[8] predict distribution of the type as that in Eqs (*6*), (*7*). The boundary condition (*2*), however, is regarded as verified by results of preceding communication[3].

Evaluation of Parameter B

Fitting the whole experimental and theoretical profiles of density of wetting was used previously[3] to evaluate B and the value satisfying the least sum of square deviations was taken as the result. A point against this approach is a large consumption of computer time and severe requirements on the quality of data. Even then the results may be distorted by using C and To which need not be quite accurate and the deviation is compensated by the shift in B under the minimum sum of squares. To evaluate B we shall make use of a method proposed in principle by Dutkai and Ruckenstein[5]. This method is extended to both types of initial wetting and modified to check the limitations of the height of layer. The authors[5] proposed a boundary condition which differs from Eq. (*2*) only formally. They assume that on a low layer of packing the density of wetting near the wall ($r = 1$) is negligible in comparison with the product C W. Under these conditions and with the aid of:

$$\mathrm{d}W/\mathrm{d}z = -2(\partial f/\partial r)\,, \quad r = 1 \tag{13}$$

the boundary condition (*2*) may be integrated to give:

$$W^{\mathrm{w}} \approx \exp\left(-2\mathrm{BC}\, z\right). \tag{14a}$$

Making an analogous simplification in the case of the wall distributor, one obtains by integrating Eq. (*2*):

$$W^{\mathrm{u}} = -2\mathrm{B}\, z\,. \tag{14b}$$

The build-up of the wall flow at uniform initial wetting as well as its reduction at initial wetting of the wall proceeds at the beginning very rapidly and accordingly only low layers of packing may be used. This is associated though with the shortcoming of having only a small number of packing pieces in contact with the wall. For packings used in this work the maximum permissible height of the layer would amount only to 2–3 times of d_{p}. The limited number of contacts realizing the exchange of liquid together with end effects (irregularity of packing on the top and the grid) would certainly affect adversely the results. Furthermore, according to our experience[3], local flooding of packing may occur.

To circumvent these disadvantages at least partially, we shall assume that the density of wetting near the wall, $f(r = 1)$, is equal $1 - W$. This assumption is a simplification but in initial stages of the process certainly well fulfilled. Substituting for $f(r = 1)$ in Eq. (*2*) and making use of (*13*) one can again integrate with the result:

$$W^{\mathrm{w}} \approx 1/(1 + \mathrm{C}) + \mathrm{C}/(1 + \mathrm{C}) \exp\left[-2\mathrm{B}(1 + \mathrm{C})\, z\right]. \tag{15a}$$

Similarly for the uniform wetting:

$$W^{\mathrm{u}} \approx 1/(1 + \mathrm{C}) - 1/(1 + \mathrm{C}) \exp\left[-2\mathrm{B}(1 + \mathrm{C})\, z\right]. \tag{15b}$$

A principal advantage of these approximate solutions is that they provide physically correct values in the limit $z \to \infty$. This gives hope that there exists an upper limit for the error. Indeed, Table I gives the values computed for B = 6, C = 3 from Eqs (*14a,b*) and (*15a,b*). It is seen that Eqs (*14a,b*) give physically meaningless values

TABLE I

The Wall Flow at Initial Uniform and Wall Distribution Computed for B = 6, C = 3 and Several Values of To from Analytical Solutions and Approximate Expressions

To	Analytical solution		Eqs (*15a,b*)		Eqs (*14a,b*)	
	W^w	W^u	W^w	W^u	W^w	W^u
0·01	0·789	0·070	0·715	0·095	0·696	0·120
0·02	0·669	0·110	0·538	0·154	0·486	0·240
0·03	0·588	0·137	0·438	0·191	0·340	0·360[b]
0·04	0·529	0·157	0·360	0·212	0·236[a]	0·480[b]
0·05	0·485	0·172	0·318	0·227	0·165[a]	0·600[b]
0·10	0·365	0·212	0·256	0·248	0·027	1·200[b]

[a] Smaller than the limit $W^w(z = \infty)$; [b] greater than the limit $W^u(z = \infty)$.

already for To > 0·03($W(z = \infty) = 0{\cdot}25$ for C = 3). For a given height of packing ($z \equiv$ To) one obtains for B the following expressions:

$$B^w = 1/(2(1 + C)\,To)\,\lg\left[C/((1 + C)\,W^w - 1)\right] \qquad (16a)$$

and

$$B^u = -1/(2(1 + C)\,To)\,\lg\left[1 - (1 + C)\,W^u\right]. \qquad (16b)$$

To evaluate B from these expressions the parameters C and To has to be known. Let us inspect therefore the sensitivity of Eqs (*16a,b*) to the accuracy of C and To. In case of To the relation is very simple and the error of B grows in direct proportion with the relative error of To. Denoting the error of C as ΔC then for the wall distributor we arrive at two limiting cases:

$$\Delta B^w/\Delta C \approx dB^w/dC = \begin{cases} \to -B/C, & \text{for} \quad To \to 0 \\ \to -\infty, & \text{for} \quad To \to \infty\,. \end{cases} \qquad (17a)$$

For the uniform distributor we have:

$$\Delta B^u/\Delta C \approx dB^u/dC = \begin{cases} \to 0, & \text{for} \quad To \to 0 \\ \to \infty, & \text{for} \quad To \to \infty\,. \end{cases} \qquad (17b)$$

For both types of initial wetting we find that the sensitivity of B to the error of C is the smallest for low layers of packing. As can be expected, the rate of transfer of liquid between the wall and packing diminishes with the approach to the steady state. The experiments on high layers of packing thus carry little information about the dynamics of exchange of liquid between the packing and wall. From measurements at two types of initial distribution using Eqs (*16a,b*) we thus get two values of B. The discrepancy between both values will depend on the accuracy of measurement, the appropriatenes of the model and variability of C and To. By simple arithmetic we find that Eqs (*16a,b*) give two identical values of B provided that C was evaluated from Eq. (*9*)

($r_1 = 0$ and $r_2 = 1$) and the same experimental data. From the balance of liquid we can change over from $M(0,1)$ to the wall flow with the result:

$$C = (1 - W^{w})/W^{u} . \quad (18)$$

Yet, this value need not be the most suitable. It is noted that for an infinite layer the solution given by Eq. (*3*) is trivial and for initial wetting of the wall (Eq. (*4*) simplifies to an expression independent of B. This fact manifests itself in solutions for the wall flow Eqs (*15a,b*) by the product B(1 + C) in the exponent. Consequently, if any of the parameters B, C is very large the other loses its importance. In the limit $C \to \infty$ the packing is free of the wall effect and the solution is trivial.

EXPERIMENTAL

The measurement of the profiles of density of wetting was carried out using the generally adopted technique. The packing rests on a set of concentric cylindres forming concentric annuli and the liquid is collected in measuring vessels. In contrast to our previous apparatus[2-4], measuring the volume of liquid drained from the packing in a known period of time, the time necessary to fill the collecting vessels was measured in this work. The floats in the collecting vessels controlled the counters connected to a pulse generator (6 per second). The set of cylindres divided the bottom cross-section into 11 annular areas about 10 mm wide and a central circular area. There were 13 collecting vessels altogether, the thirteenth being for the wall flow. There were three positions of the float delimiting volumes of about 0·5, 1 and 2 litres in each vessel. The selection of the volume to be collected was made according to the type of distributor used. The arrangement used for separation of the wall flow is sketched in Fig. 1. An advantage of this arrangement, in contrast to those described in the literature selecting a certain empirical radius smaller than that of the column to collect the wall flow, is that the proper function of the separator is independent of the size of packing. A device described in principle in paper[3] was used as the uniform distributor. It was a vessel with its outer diameter corresponding to the inner diameter of the column. The bottom of the distributor was equipped with hollow rivets arranged in a square (10 mm) pitch. There were 7 mm long nylon fibre loops mounted in each rivet. These loops were to ensure a uniform function even at very low velocities of liquid. The wall distributor was again

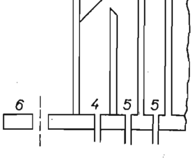

FIG. 1

Sketch of Experimental Arrangement for Separation of the Wall Flow

1 Column wall; *2* piece of packing; *3* separator of wall flow; *4* collector of wall flow; *5* collector of flow from packing; *6* flange.

a brass vessel fitting the column. There were 1 mm diameter openings 5 mm apart on the periphery of the distributor. The bottom part with the openings was of slightly smaller diameter forming a 1 mm wide ring-shaped gap forcing the liquid to form a film on the wall. A satisfactory function of the distributor was observed to a minimum velocity $f_0 = 0{\cdot}001$ m/s. At lower velocities the pressure drop was not sufficient to form a continuous liquid jet in the openings of the distributor. The column was a glass cylinder 291 mm diameter. The packings used were glass spheres 15 and 20 mm diameter and porcelain Raschig rings 15 and 25 mm diameter. Water at 25°C was used in all cases as liquid. The column was filled by dumping dry packing and levelling the top. All experimental runs were started from the largest selected flow rate of liquid. Before each experimental series the packing was flooded. All measurement were carried out without gas phase and the mean density of wetting ranged between $0 < f_0 < 0{\cdot}008$ m/s. After filling the column a series of measurement was carried out, each run at a given velocity twice. Having completed the series another type of distributor was placed in the column and the whole series of experiments performed. The column was then filled with the packing to the next mark of height and measurements with both distributors carried out. Each packing was measured at three different heights of layer (spheres $d_p = 15$ mm at four heights). Completing the measurements on all preselected heights the column was emptied and repacked and the whole routine repeated three-times. The experimental values of times necessary to fill the vessels were averaged (6 values altogether: 3 redumpings duplicated). According to the theory worked out earlier[2], the 12 "basic" annuli can form a total of 78 "basic and derived" annuli by adding the volumes of liquid collected in neighbouring annuli. The average radius, r_m, derived[2] from assumption of linearity of the profile of density of wetting over the range $\langle r_i - r_e \rangle$ is then

$$r_m = 2/3[r_e + r_i^2/(r_e + r_i)]\,, \qquad (19)$$

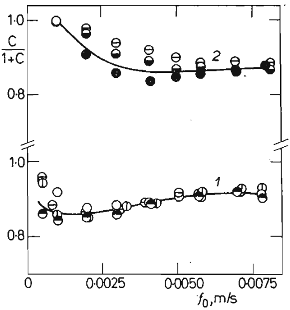

FIG. 2

Dimensionless Equilibrium Wall Flow C/(1 + C) at Various Mean Densities of Wetting Evaluated from Experiments on a Layer of Spheres of Different Height

1 d_p 15 mm; *2* d_p 20 mm; ○ *h* 200 mm; ⊖ 300; ⦶ 400; ◒ 500; ◓ 570; ● 875.

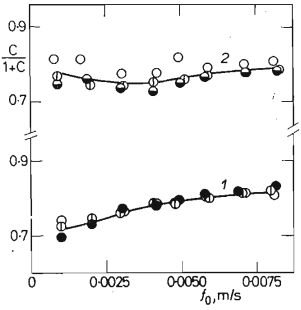

FIG. 3

Dimensionless Equilibrium Wall Flow C/(1 + C) at Various Mean Densities of Wetting Evaluated from Experiments on a Layer of Raschig Rings of Different Height

1 d_p 14 mm; *2* d_p 25 mm; ○ *h* 300 mm; ⦶ 500; ◒ 1 000; ● 1 165.

r_e and r_i are the inner and outer diameters of the collecting annulus. From the total of 78 annuli we took as most suitable those formed by at most 4 neighbouring annuli. By adding a greater number of annuli the requirement of linearity of f in $\langle r_i - r_e \rangle$ could be seriously violated. In contrast, it is expected that the results computed from data of the basic annuli may carry a substantial error because $(r_e - r_i)$ equals approximately $d_p/2$ and according to our findings[2] $(r_e - r_i) > d_p$ is needed to eliminate most severe deviations.

RESULTS AND DISCUSSION

Evaluation of Parameter C

The expression in Eq. (9) was used to evaluate C. By putting $r_2 = 1$ and plotting $(1 - r_1^2 - M^u(r_1, 1))$, *versus* $M^w(r_1, 1)$ while r_1 takes the dimensionless values of radii of the collecting annuli a straight line through origin with the slope $1/C$ was obtained. The best straightline served to compute C. Figs 2 and 3 show the values $C/(1 + C)$ for all packings used in dependence on the mean density of wetting. The curves were drawn through points obtained by averaging the results on different heights of layer at approximately equal f_0 and weighed by the standard deviation of evaluation. Thus a greater statistical weight is given to experiments with a smaller variance and mostly to experiments on higher layers of packing which are more suitable. From Figs 3 and 4 it is seen that for medium and higher mean densities

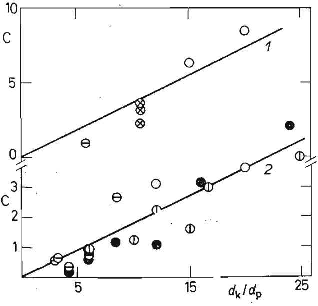

FIG. 4

C as a Function of (d_k/d_p)

1 Spheres; 2 Raschig rings; ○ this work; ⊗ Staněk, Kolář[3]; ⦶ Dutkai, Ruckenstein[5]; ⊖ Zarzycki[10]; ● Porter, Templeman[7].

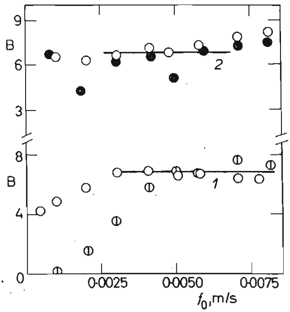

FIG. 5

Experimental Values of B at Various Mean Densities of Wetting

1 Spheres; *2* Raschig rings; ○ d_p 15 mm; ⦶ 20; ⊖ 25.

of wetting C can be regarded reasonably as constant. Certain trends apparent at higher densities of wetting are caused by inconstancy of D, which has been known to display certain dependence on f_0 at highly nonuniform wetting caused by local flooding. The tendency toward local flooding naturally increases with the column diameter because the amount of liquid brought into the column increases with d_k^2 but the circumference with d_k only. The changes of C with the mean density of wetting at low f_0 can be accounted by the effect of different wettability of the material of wall and packing.

Certain conclusions can be drawn from model due to Zarzycki[10] and Hobler[11], The author[10] represents the packing by a zig-zag vertical surface P_p wide, its total surface area being equal to the total surface of the packing. The slope of the model packing equals α. The column wall is represented by a flat vertical surface P_w wide. P_w equals the circumference of the column. Assuming the laminar flow of liquid on both surfaces, the total energy of liquid per unit height of column, E, equals the sum of the kinetic and surface energy of both streams and it is given by:

$$E = (P_w X_w \gamma_l T_w^5)/15L^3 + P_w X_w(\sigma_{wl} + \sigma_{lg}) + \\ + P_w(1 - X_w)(\sigma_{lg} \cos \Theta_w + \sigma_{wl}) + \\ + P_p X_p \gamma_l T_p^5/15L^3 + P_p X_p(\sigma_{pl} + \sigma_{lg}) + \\ + P_p(1 - X_p)(\sigma_{lg} \cos \Theta_p + \sigma_{pl}) \,, \tag{20}$$

where T_w and T_p are the respective thicknesses of films on the wall and packing. For X_p, X_w giving the fraction of the surface area of either surface covered by film one can write[11]:

$$X_w = \mathrm{Re}_w/\mathrm{Re}_{wc} \,, \quad 0 \leqq \mathrm{Re}_w \leqq \mathrm{Re}_{wc} \,; \quad X_p = \mathrm{Re}_p/\mathrm{Re}_{pc} \,, \quad 0 \leqq \mathrm{Re}_p \leqq \mathrm{Re}_{pc} \,. \qquad (21), (22)$$

Above the critical value of the Reynolds number the surface is completely covered by film. Let us assume now that the column is operated under very low density of wetting when neither of the surfaces is perfectly covered: $X_w < 1$, $X_p < 1$. Substituting for X_p, X_w, T_p and T_w in Eq. (20) and eliminating one of the Reynolds numbers by introducing a total Reynolds number as:

$$\mathrm{Re} = 4Q/(P_w \nu) = \mathrm{Re}_w + \mathrm{Re}_p P_p/P_w \,, \tag{23}$$

we find that the equilibrium distribution of liquid between wall and packing is determined by following inequality:

$$\sin \alpha (1 - \cos \Theta_w)/(1 - \cos \Theta_p) \lesseqgtr 1 \,. \tag{24}$$

If the upper sign of inequality holds the minimum energy occurs when all liquid trickles down the wall. With the lower sign of inequality the minimum occurs when all liquid flows over the packing. Let us assume now that the total Re and wettability of both materials are such that only the wall is thoroughly covered by the film: $X_w = 1, X_p < 1$. The total energy is then obtained from Eq. (*20*) by substituting for X_p, T_p, T_w and putting X_w equal unity. For the minimum energy we get after eliminating again one of the Re numbers:

$$\mathrm{Re_w} = \mathrm{Re_{pc}} \sin \alpha \,. \tag{25}$$

For the ratio of liquid rates on the packing and wall we have:

$$Q_p/Q_w = \mathrm{Re}/(\mathrm{Re_{pc}} \sin \alpha) - 1 \,. \tag{26}$$

A constant flow rate is flowing down the wall and the portions of liquid added by increasing the mean density of wetting are transferred onto the packing. In the opposite case, *i.e.* complete covering of the packing: $X_w < 1, X_p = 1$, we get analogously

$$\mathrm{Re_p} = \mathrm{Re_{wc}} \sin \alpha \,, \tag{27}$$

and

$$Q_w/Q_p = P_w\mathrm{Re}/(P_p\mathrm{Re_{wc}} \sin \alpha) - 1 \,. \tag{28}$$

A constant flow rate is flowing down the packing and the portions of liquid added by increasing the mean density of wetting are transferred onto the wall. Finally, consider a high Reynolds number ensuring complete covering of both surfaces: $X_p = X_w = 1$. Under the minimum energy condition we get for the wall flow

$$Q_w/Q = \mathrm{Re_w}/\mathrm{Re} = P_w/(P_w + P_p \sin \alpha) \tag{29}$$

and hence for C:

$$\mathrm{C} = \sin \alpha P_p/P_w \,. \tag{30}$$

At strict adherence to this model the boundary condition (*2*) could not be correct, owing to the predicted dependence of equilibrium distribution on the mean density of wetting at low wettings. But, according to our experience, resulting behaviour of liquid under such conditions is governed by the presence of surface active agents on the surface of packing and/or wall rather than by contact angles appearing in Eqs (*24*), (*26*), (*28*). This statement is supported by variable behaviour of systems where the material of column, packing and liquid does not change. In a particular case of Raschig rings, (Fig. 3), for smaller rings C decreases in limit $f_0 \to 0$, while it seems to increase on 25 mm packing. Similar phenomenon has been observed earlier[3] where a similar plot C/(1 + C) *versus* f_0 in different experimental runs on 10 mm glass spheres tended to both smaller and larger values in limit $f_0 \to 0$. The importance of wettability for liquid distribution at low f_0 thus rests in formation of preferential channels through the packing controlled by probability of meeting the spots contaminated by surface active agents. This explains higher variability of parameters observed at low densities of wetting. With the variations of distribution on a packing of the same type and size but different origin, probabilistic model need not be rejected because formation of preferential paths as well as the presence of surface active agents may be regarded as a random variable.

Typical values of the parameter C are respectively 8·44 and 6·32 for spheres 15 and 20 mm diameter. Similarly, the respective values for 15 and 25 mm diameter Raschig rings are 3·66 and 3·12. For a spherical packing the quantities appearing in Eq. (*30*) can be related to the diameter of column and packing:

$$C = Q_p/Q_w = \sin \alpha \, 1{\cdot}5(1 - \varepsilon)(d_k/d_p) \,. \qquad (31)$$

Analogously, a simplified geometry (neglecting curvature) relates C for Raschig rings to the first power of the column to diameter ratio:

$$C = \sin \alpha \, 0{\cdot}5(1 - \varepsilon)(d_p/T)(d_k/d_p) \,, \qquad (32)$$

where (d_k/T) ratio may be regarded as constant for construction reasons and the void fraction of similar packings is independent of d_p. Jameson[12,13] reports direct proportionality between C and the ratio $(d_k/d_p)/((d_k/d_p) + 1)$ which approximates our results with increasing (d_k/d_p). Considering the direct proportionality between C and (d_k/d_p) as justified, additional interesting conclusions may be drawn. Substituting for C we get

$$C = (d_p/T_w)(f'(h = \infty)/V_w)(d_k/d_p) \,, \qquad (33)$$

which is an expression suggesting similarity of the geometry of flow (size of packing and thickness of film) and the hydrodynamic similarity (superficial velocity on packing and velocity of film) at the geometric similarity of the column and packing.

Fig. 4 (straight line *1*) shows our results of C obtained on a packing of spheres supplemented by earlier[3] results with various liquids and the results from work[10] in column 42 mm diameter. The points are reasonably correlated by direct proportionality with (d_k/d_p). The best straightline has a slope 0·365 and the correlation coefficient equals 0·9760 for $n = 6$ points. Otherwise, the earlier results[3] do not confirm Eq. (*30*) which provides no effect of physical properties of liquid on C. Straight line 2 correlates our results on a packing of Raschig rings supplemented by measurements of other authors[5,7,10]. The straightline through the origin gives a satisfactory fit. The best slope found is 0·181 and the correlation coefficient equals 0·9397 ($n = 21$ points). A more general regression $C = k(d_k)^i (d_p)^j$ gave (all dimensions in mm) $k = 0{\cdot}0875$, $i = 1{\cdot}196$, $j = -1{\cdot}136$. Clearly, in view of experimental error the deviation of i and j from unity is not significant. Thus the direct proportionality seems well founded even though the values for the column diameter ratio less than unity are physically meaningless (the non-uniformity of the bed restricts the usefulness of the correlation to even higher d_k/d_p ratios).

Substituting the best slopes of C ≈ (d_k/d_p) in Eqs (*31*), (*32*) one obtains numerical values for the average slope of the model packing. The results for spheres are ($\varepsilon = 0{\cdot}4$) $\alpha = 24°$, for rings ($\varepsilon = 0{\cdot}7$, $(d_p/T) = 7$) $\alpha = 10°$. These relatively small values suggest that the flow of liquid on the packing is slow, which is probably due to retardation in the points of contact of packing. Particularly low values of α for Raschig rings would mean that a substantial portion of the rings is oriented with its axis horizontally. It seems more likely though that the total surface of the rings appearing in Eqs (*30*), (*32*) is not in reality accessible to flow for geometry reasons even at high densities of wetting. Approximating the surface of the ring accessible to flow by its outer surface (πd_p^2) one obtains for the average slope $\alpha = 20°$ which is almost equal to the value for spheres. A correlation of C for a general type of packing based on this speculation is then:

$$C = 0{\cdot}1(1 - \varepsilon)\, K_s \tau (d_k/d_p)\,, \qquad (34)$$

where τ is a fraction of the surface accessible to flow (for spheres $\tau = 1$). In view of a limited number of packings used in this work this relation must be used with caution.

Evaluation of Parameter B

Parameter B was evaluated from experimental data obtained on layers 200 and 300 mm high. Eqs (*16a,b*) were used, in spite of the fact that their deviation from analytical solutions toward lower values (Table I) is not negligible. This, however,

Table II
Values of B Computed from Data of Dutkai and Ruckenstein[5]

d_p, mm	d_k, mm	B_1	C	To	B_2	B_3
			Raschig rings			
10	150	6·23	1·63	0·01227	6·95	4·52
15	150	4·61	1·25	0·01742	5·04	4·65
25	150	3·84	0·96	0·02436	4·24	5·48
10	250	7·21	4·00	0·00442	7·21	4·69
15	250	5·41	3·00	0·00627	5·53	5·10
25	250	4·67	2·23	0·00877	4·85	6·26
			Intalox saddles			
15	150	6·97	1·44	0·01502	7·84	—
15	250	7·96	3·54	0·00541	8·25	—

compensates for the effect of possible local flooding on the top caused by the wall distributor. Furthermore, the variation of results is reduced by an increased number of elements of packing in contact with the wall. The values of To were computed from previous results[4] indicating that within experimental error the quantity D for a given packing is independent of d_p. The values of D found[4] were $D = 1{\cdot}383$ and 2·123 mm for spheres and Raschig rings, respectively. The results are shown graphically in Fig. 5. A decrease of B observed for spheres at mean densities of wetting below 0·003 m/s was caused by increased values of C used for evaluation. As has been mentioned, packings characterized by a large value of C depend little on B. The results on Raschig rings may be well regarded as independent of f_0. Typical values of B are 6·56 and 6·82 (average 6·68) for spheres 15 and 20 mm diameter respectively. Similarly we get 7·05 and 6·82 (average 6·95) for rings 15 and 25 mm diameter. It can be concluded, however, that the change due to different size for a given packing is within experimental error; the difference between the averages for both types of packing does not seem important either. These results are in reasonable agreement with the value 6·126 for 10 mm spheres reported earlier[3]. Table II gives a comparison of the values computed from data of Dutkai and Ruckenstein[5]. The values denoted as B_1 were computed from Eq. (*14a*), B_2 from (*16a*). The values B_1 (or B_2), which display certain variation with d_p, are thus at variance with the findings of this

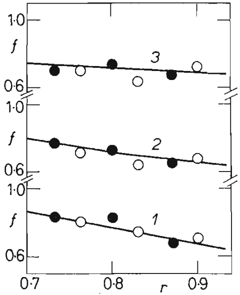

FIG. 6

A Comparison of Experimental and Predicted Distribution of Density of Wetting Near the Wall at Uniform Initial Wetting of a Layer of Raschig Rings of Different Height

$f_0 = 0{\cdot}003$ m/s; d_p 25 m; *1* h 300 mm; *2* 500; *3* 1000. Results obtained by adding: ○ 3 basic annuli; ● 4 basic annuli.

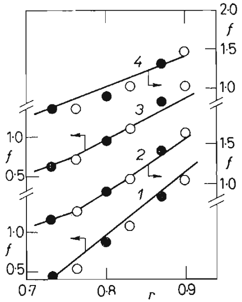

FIG. 7

A Comparison of Experimental and Predicted Distribution of Density of Wetting Near the Wall at Wall Initial Wetting of a Layer of Spheres of Different Height

$f_0 = 0{\cdot}004$ m/s; d_p 15 mm; *1* h 200 mm; *2* 300; *3* 400; *4* 570. Results obtained by adding: ○ 3 basic annuli; ● 4 basic annuli.

work. The values B_3, computed as B_2 using D from work[4], indicate that the dependence on d_p comes from To (or D). Neglecting the variations of B_3 with d_p we find agreement with these authors[5] in that parameter β of the boundary condition is independent of d_p since $B = \beta R/D$. The source of discrepancies is therefore the quantity D. A direct comparison of our results with those from work[5] indicates a satisfactory agreement only for large packings, particularly in column $d_k = 250$ mm, *i.e.* under conditions similar to those of this work. The discrepancies may be due to different way of filling the column affecting strongly the distribution parameters. From the results of Dutkai and Ruckenstein in Table II it further follows that for a given packing B does not depend on d_k. Together with the independence on d_p these are very practical findings which, of course, need some more experimental support.

The theoretical distributions of liquid computed with the aid of parameters from this work exhibit a good agreement with experimental profiles. Typical curves and experimental points in the vicinity of the wall, *i.e.* in region affected mostly by parameters of the boundary condition, are plotted in Figs 6 and 7 for several heights of layer, both types of packing and both types of initial wetting. The agreement evidences the utility of the knowledge of the parameters of distribution.

LIST OF SYMBOLS

$B = \beta R/D$	parameter of boundary condition (2)
$C = \pi R^2 \gamma$	parameter of boudary condition (2)
D	coefficient of radial spreading of liquid (L)
E	energy of liquid per unit height of packing ($M L T^{-2}$)
d_k	column diameter (L)
d_p	packing diameter (L)
$f = f'/f_0$	dimensionless density of wetting
f^u, f^w	function of dimensionless density of wetting at uniform (u) and wall (w) initial wetting
f'	density of wetting ($L T^{-1}$)
$f_0 = Q/(\pi R^2)$	mean density of wetting ($L T^{-1}$)
g	acceleration due to gravity ($L T^{-2}$)
h	height of packing layer (L)
J_0, J_1	Bessel function of first kind zero-th and first order
K_s	specific shape factor (surface/volume of a piece of packing at $d_p = 1$), for a sphere equal 6
$M^u(r_1, r_2), M^w(r_1, r_2)$	fractional dimensionless flow rate between r_1 and r_2 at uniform (u) and wall (w) initial wetting
P_p, P_w	total surface of packing per unit height of column (p), periphery of column (w) (L)
Q	total volume of liquid brought into column per unit time ($L^3 T^{-1}$)
Q_p, Q_w	flow rates of liquid on packing (p) and wall (w) ($L^3 T^{-1}$)
R	radius of column (L)
$Re = 4Q/(P_w \nu)$	total Reynolds number
$Re_p = 4Q/(P_p \nu)$	Reynolds number for packing

$\mathrm{Re}_w = 4Q/(P_w \nu)$	Reynolds number for wall
$\mathrm{Re}_{pc} = 4/3[45\sigma_{lg}(1 - \cos \Theta_p)/(2\gamma_l L^2)]^{3/5} (\sin \alpha)^{3/5}$	critical Reynolds number for packing
$\mathrm{Re}_{wc} = 4/3[45\sigma_{lg}(1 - \cos \Theta_w)/(2\gamma_l L^2)]^{3/5}$	critical Reynolds number for wall
$r = r'/R$	dimensionless radial coordinate
r'	radial coordinate (L)
r_e, r_i, r_m	external, inner and mean dimensionless radius of collecting annulus
T	thickness of wall of Raschig ring (L)
$T_p = (3/4)^{1/3} L[\mathrm{Re}_p/(X_p \sin \alpha)]^{1/3}$	thickness of liquid film on packing (L)
$T_w = (3/4)^{1/3} L[\mathrm{Re}_w/X_w]^{1/3}$	thickness of liquid film on wall (L)
$\mathrm{To} = Dh/R^2$	dimensionless height of packing (parameter of distribution)
V_w	velocity of liquid on wall ($\mathrm{L\,T^{-1}}$)
$W = W'/Q$	dimensionless wall flow
W'	wall flow ($\mathrm{L^3\,T^{-1}}$)
W^u, W^w	function of dimensionless wall flow at uniform (u) and wall (w) initial wetting
X_p, X_w	fraction of surface of packing (p) and wall (w) covered by film
$z = Dz'/R^2$	dimensionless vertical coordinate
z'	vertical coordinate (L)
α	mean "slope" of packing (deg)
β	parameter of boundary condition
γ	parameter of boundary condition ($\mathrm{L^{-2}}$)
γ_l	specific weight of liquid ($\mathrm{M\,L^{-2}\,T^{-2}}$)
ε	void fraction
τ	fraction of surface of packing accessible to flow (for spheres $\tau = 1$)
$\sigma_{lg}, \sigma_{pl}, \sigma_{wl}$	interfacial tension, gas (g), liquid (l), packing (p), wall (w) ($\mathrm{M\,T^{-2}}$)
Θ_p, Θ_w	contact angle, packing (p), wall (p) (deg)
ν	kinematic viscosity of liquid ($\mathrm{L^2\,T^{-1}}$)

REFERENCES

1. Staněk V., Kolář V.: This Journal *32*, 4207 (1967).
2. Staněk V., Kolář V.: This Journal *33*, 1049 (1968).
3. Staněk V., Kolář V.: This Journal *33*, 1062 (1968).
4. Staněk V., Kolář V.: This Journal *33*, 2636 (1968).
5. Dutkai E., Ruckenstein E.: Chem. Eng. Sci. *23*, 1365 (1968).
6. Porter K. E., Barnett V. D., Templeman J. J.: Trans. Inst. Chem. Eng. *46*, T 74 (1968).
7. Porter K. E., Templeman J. J.: Trans. Inst. Chem. Eng. *46*, T 80 (1968).
8. Porter K. E., Jones M. C.: Trans. Inst. Chem. Eng. *41*, 240 (1963).
9. Perktold F.: Angew. Chem. *B 19*, 184 (1947).
10. Zarzycki R.: Inzynieria Chemiczna *1*, 85 (1971).
11. Hobler T.: Chem. Stos. *1B*, 145 (1964).
12. Jameson G. J.: Trans. Inst. Chem. Eng. *44*, T 198 (1966).
13. Jameson H. J.: Trans. Inst. Chem. Eng. *45*, T 74 (1967).

Translated by author (V. S,).