TWO-PHASE COUNTERCURRENT FLOW THROUGH A BED OF PACKING. VIII.*

EFFECT OF THE GEOMETRICAL PACKING SHAPE (SPHERE, RASCHIG RINGS, HYPERFIL)

Z. Brož and V. Kolář

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

Received April 8th, 1971

The basic theoretical relations for calculation of liquid holdup and gas pressure drop, verified experimentally earlier on a packing of glass spheres, are also valid for packings of different geometrical shapes, dimensions and porosities after arrangement which includes the effect of porosity. With a wire Hyperfil packing of large porosity was observed and described irregular distribution of liquid holdup due to successive flooding of the packed bed from the bottom. An analysis was made of the correlation data at flooding and the relation of Gelbe was verified for liquid holdup at zero pressure drop over the bed of Raschig rings.

The already published theoretical model[1] was used earlier[2-7] for mathematical evaluation of experimental data on liquid holdup and pressure drop at a two-phase countercurrent liquid and gas flow through a bed of glass spheres. The suitability of this theoretical approach, applied until now on the packing of simple geometrical shapes, is verified here on packings of different shapes, dimensions and porosities. The measurements were made with porcelain Raschig rings of five sizes and with the Hyperfil packing of large porosity as the representative of a packing with completely different structure. Moreover, data from literature were evaluated so that by their comparison with behaviour of packed spheres a generalization of suggested relations was possible resulting in a reduction of number of empirical relations published earlier[6,7] which were necessary for expression of the flow characteristics of phase flow in a packed bed.

EXPERIMENTAL

The method of measuring the column weight with the packing at the countercurrent phase flow enables to determine the liquid holdup and pressure drop of gas across the packed bed. Earlier described experimental unit[2] was modified (Fig. 1) by suspending the closed cylinder *39* from the two-armed lever *40* while the column with the packing is situated at the other side *9*. Under the

* Part VII: This Journal *32*, 1666 (1972).

cylinder situated in a hydraulic seal *54* was introduced pressure from the position *22* below the grid *23* of the column with the packing by piping *55*, *58* so that force acting on the column in the plane of the lower flange *23* which had to be considered earlier in calculation of the liquid holdup was compensated. The accuracy of measurement of liquid holdup is not affected by possible errors in measurements of pressure drop. Further arrangements concerned additional pipings for measurements of gas and liquid flow rate.

The measuring procedure was similar to that one described earlier[2] with wetting of the packing made by its flooding at the measured liquid flow rate for about 15 min. Then the gas flow was stopped, after twenty minutes the liquid holdup without the gas flow was determined and measurements were carried out with the increasing gas flow up to the flooding at which a liquid

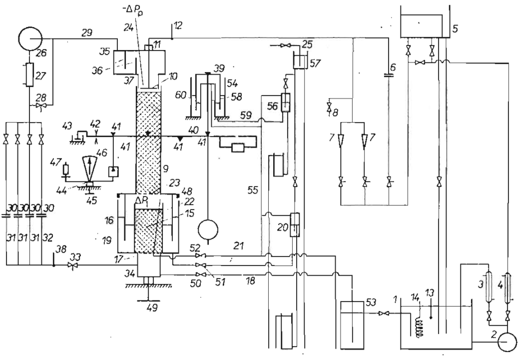

FIG. 1

Flow Sheet of the Experimental Station

1 Tank, *2* centrifugal pump, *3*, *4* liquid cooler, *5* tank with constant liquid level, *6* 2 orifices for liquid flow, *7* rotameters, *8* pipe for calibration, *9* column made of perspex, *10* rotating distributor, *11* motor 20 rev./min, *12* thermometer for liquid, *13* contact thermometer, *14* electrical heating, *15* packed bed of Raschig rings for distribution and humidification of gas, *16* hydraulic seal, *17* grid in the hydraulic seal, *18* liquid outlet, *19* liquid level in hydraulic seal, *20* overflow liquid from hydraulic seals, *21* liquid piping, *22* pressure tap below the packed bed, *23* grid plate of the column, *24* pressure tap above the packed bed, *25* water supply from the main, *26* blower 1100 Torr, *27* air cooler, *28* side stream, *29* blower inlet, *30* 4 orifices for gas flow, *31* air piping ID 50 mm, *32* air piping ID 25 mm, *33* gate valve, *34* air inlet into the hydraulic seal, *35* separator of liquid carry-over, *36* baffles, *37* cylinder, *38* thermometer, *39* cylinder, *40* two-armed lever, *41* blades, *42* balance arrest, *43* adjustable hydraulic damping, *44* balance, *45* screw of the vertical motion of the balance, *46* pointer of the horizontal position of two-armed lever, *47* inductive primary element of position, *48* packing, *49* screw, *50*, *51*, *52* closing valves, *53* hydraulic seal, *54* hydraulic seal, *55* piping, *56* overflow vessel, *57* overflow tank, *58* air piping, *59* water supply into the hydraulic seal, *60* liquid level in hydraulic seal.

layer formed above the packing or at low liquid flow rates with liquid drops carried away from the bed. With the Hyperfil packing flooding always started at the bottom of the column which will be further discussed in more detail. Measurement of the liquid holdup was then repeated without gas flow. As the packing were used unglazed porcelain Raschig rings of 8, 15, 25 and 35 mm diameter in a column of 0·19 m diameter and packing height of 1 m. Another packing used in the experiments was the wire packing of trade mark Hyperfil supplied in cylinders of 1000 mm diameter and height. The cylinders were made by combination of a double split grip weaved by 5 × × 7 mm stitch of rope formed by 8 stainless steel wires of 0·12 mm diameter. It was assumed for calculation of the packing surface per unit of bed volume that at wetting the rope by liquid the surface is considered as a unit *i.e.* not as individual wires by which it is formed. As the mean diameter of the rope was chosen the value 0·4 mm. The specific surface of the packing and its porosity were determined from the packing weight and density of material. The packing characteristics and the range of measured liquid flow rates are given in Table I. The system used was water–air at 25°C.

RESULTS

The shape of dependence of liquid holdup on the gas flow rate with the liquid flow rate as the parameter is similar for all dimensions and geometrical shapes of packings. In Figs 2–4 are given examples of such dependences for two dimensions of Raschig rings and for the packing Hyperfil. Similar shapes have also the dependences of liquid holdup on packing of glass spheres[2]. The dependence of liquid holdup on gas

TABLE I

Packed Bed Characteristics and Range of Measured Liquid Flow Rates

Packing								
d_j	d_i	h	a	e	d_e	z_{st}[a]	$(G_l)_{min}$	$(G_l)_{max}$
			Raschig rings[b], column diam. 0·1903 m, bed height 1 m					
8·14	4·72	8·65	591·3	0·6234	0·001691	0·0532	0·306	19·9
15·2	10·3	14·9	329·1	0·6888	0·003039	0·0192	0·306	19·9
19·9	14·0	20·5	247·9	0·7052	0·004034	0·0134	0·833	19·9
24·9	17·8	24·8	199·1	0·7155	0·005023	0·0074	0·833	21·5
35·1	26·6	34·5	131·6	0·7546	0·00760	0·0058	3·61	21·5
			Hyperfil, column diam. 0·1098 m, bed height 0·920 m					
—	—	—	1 058	0·9363	0·000945	0·0232	4·12	61·6

[a] The average time of liquid drainage from the packed bed is about 14 h. [b] Dimensions of Raschig rings were determined by measuring 200 elements of the packing. Specific surface and packing porosity were determined from the weight, dimensions and density of packing. Porosity was also measured directly.

flow rate was described earlier[1,3] by equation

$$\frac{2g\varrho_1^2 d_e z^3}{G_1^2} = \vartheta + \eta \left(\frac{G_g}{G_1}\right)^2 \frac{\varrho_1}{\varrho_g} \left(\frac{z}{e - z}\right)^3. \qquad (1)$$

In Fig. 5 is plotted the dependence of liquid holdup on the packing of Raschig rings of 8 mm diameter for low liquid flow rates and in Fig. 6 for high liquid flow rates. It is obvious that the dependences for individual liquid flow rates are separated into two parts which may be very well approximated by linear dependences with their intersections denoted by asteriscs. The dotted line in Fig. 2 for the packing of Raschig rings of 8 mm diameter corresponds to points denoted in Figs 5 and 6 by asteriscs and it separates into two regions the dependence of liquid holdup on gas flow rate for the given liquid flow rate. At low liquid flow rates, when the liquid holdup is in a wide range of gas flow rates nearly constant, this point corresponds to the gaseous flow rate at which a more rapid increase of liquid holdup in the packing together with gas pressure drop takes place. We can say that this point is either identical or very close to the loading point which is in literature defined from the shape of the exponential dependence $\Delta P_g \sim G_g^n$. It is said that at this point the exponent changes from the original value $n = 1{\cdot}8 - 2$ to the value $n = 3 - 4$. But at high liquid flow rates the liquid holdup increases rapidly even from the zero gas flow rate, while the exponent $n = 3 - 4$ is not reached even at gas flow rates close to that of flooding. Therefore, we have defined this point of transition from the dependence in coordinates according to Eq. (1) which is hereinafter denoted as the loading point.

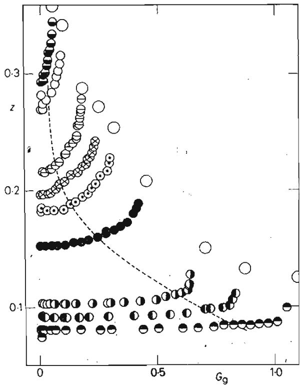

FIG. 2

Dependence of Liquid Holdup on Gas Flow Rate for Packing of Raschig Rings of D 8 mm ◒ G_1 ($kgm^{-2} s^{-1}$) = 0·306, ◐ 0·833, ◑ 1·38, ● 4·12. ⊙ 6·87, ⊗ 8·25, ⊖ 11·0, ○ 16·8, ◓ 19·9. Dotted line represents loading points, large circles the calculated liquid holdup at the flooding point.

The validity of empirical relation for liquid holdup in the loading point published earlier has been verified also for the packed bed of Raschig rings and for the Hyperfil

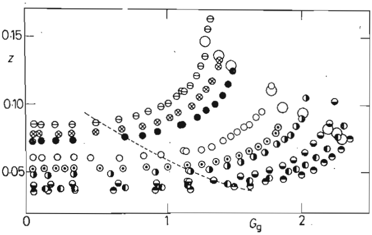

FIG. 3

Dependence of Liquid Holdup on Gas Flow Rate for Packing of Raschig Rings d 35 mm
◒ G_l (kgm^{-2} s^{-1}) = 3·61, ◐ 4·12, ◒ 4·86, ◑ 6·87, ⊙ 8·25, ○ 11·0, ● 16·5, ⊗ 19·0, ⊖ 21·5. Dotted line represents loading points, large circles the calculated liquid holdup at flooding point.

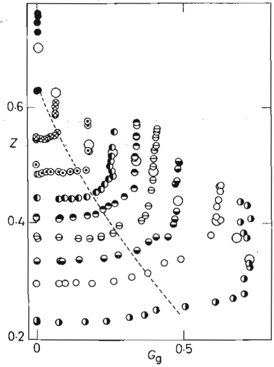

FIG. 4

Dependence of Liquid Holdup on Gas Flow Rate for Packing Hyperfil

◑ G_1 (kgm^{-2} s^{-1}) = 4·12, ○ 8·52, ◒ 12·5, ⊖ 16·9, ◒ 22·0, ◐ 29·0, ⊙ 36·5, ⊗ 49·2, ● 61·6. Dotted line represents loading points, large circles the calculated liquid holdup at flooding point.

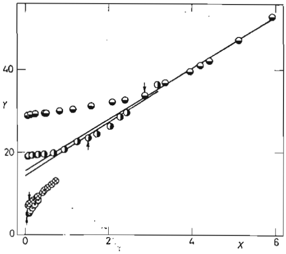

FIG. 5

Dependence of Liquid Holdup on Raschig Rings of d 8 mm and on Gas Flow Rate for Low Liquid Flow Rates

$Y = 2g\varrho_l^2 d_e z^3 / G_l^2$, $X = (G_g/G_l)^2 (\varrho_l/\varrho_g) . (z/e - z)^3$; ◒ G_l(kgm^{-2} s^{-1}) = 0·897, ◑ 1·38, ⊗ 4·12, ⊙ 6·87; the asteriscs denote loading points.

packing. It has been determined, that the relation valid for the packing of glass spheres

$$z_k = (1{\cdot}041 \pm 0{\cdot}0025) \, . \, z_0 \tag{2}$$

is valid.

The dependence of liquid holdup on gas flow rate may be approximated in variables of Eq. (*1*) in the range $0 \leqq G_g \leqq G_{gk}$ and $G_{gk} \leqq G_g \leqq G_{gz}$ by linear dependences with corresponding empirical coefficients for individual regions of gas flow rates. The empirical coefficients ϑ and η in the region above the loading point $G_{gk} \leqq G_g \leqq G_{gz}$ may be considered as independent on the gas flow rate. The coefficient ϑ thus represents the value of the coordinate of linear dependence given by Eq. (*1*) extrapolated from the region above the loading point to the zero value of abscissa ($G_g = 0$). For the coefficient ϑ then follows the relation

$$\vartheta = 2g\varrho_l^2 d_e z_e^3 / G_l^2 \, . \tag{3}$$

The coefficient has for low liquid flow rates lower value and for high liquid flow rates higher value than is the value of abscissa calculated from the experimentally determined holdup z_0 at the zero gas flow rate. For the extrapolated value of liquid holdup z_e calculated from the coefficient ϑ has been obtained a general empirical relation which is identical for all until now measured packings and physical systems in the form

$$z_e/e = 1{\cdot}044(z_0/e) - 0{\cdot}009 \, . \tag{4}$$

The earlier presented relation[6] $z_e = 1{\cdot}0375 z_0 - 0{\cdot}003$, valid only for the packing of glass spheres, is identical with relation (*4*) for $e = 0{\cdot}39$ which corresponds to the

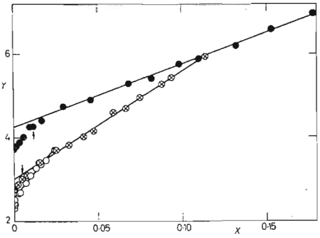

FIG. 6

Dependence of Liquid Holdup on Raschig Rings of $d = 8$ mm on the Gas Flow Rate for Large Liquid Flow Rates

● G_l (kgm^{-2} s^{-1}) = 8·25, ⊗ 11·0, ○ 16·8; the asteriscs denote loading points.

porosity of a bed of spheres. From Eq. (*4*) it is obvious that the extrapolated value of liquid holdup z_e may be smaller, equal or greater than the liquid holdup at zero gas flow rate z_0. It is possible to demonstrate that in the case of $z_e = z_0$ the earlier presented[3] empirical relation for gas pressure drop in the form

$$(\Delta P_g/l) = \xi\{G_g^2/[2\varrho_g d_e(e - z)^3]\} + \zeta \tag{5}$$

has the value of the coefficient $\zeta = 0$, from which follows for the value of the friction factor $\psi_g \equiv \xi + f(Re_g)$. Then Eq. (*1*) is valid for dependence of liquid holdup on the gas flow rate in the whole region of gas flow rates $0 \leqq G_g \leqq G_{gz}$ with the same values of coefficients ϑ and η. As is obvious from Figs 2–4, the relation $dG_{gz}/dz = 0$ is well satisfied. From it and from Eq. (*1*) was derived the relation[1,4] for gas flow rate at flooding in the form

$$\left[\frac{\eta}{\vartheta}\left(\frac{G_{gz}}{G_l}\right)^2 \frac{\varrho_l}{\varrho_{gz}}\right]^{1/4} + 1 = \left[\frac{2g\varrho_l^2 d_e e^3}{\vartheta G_l^2}\right]^{1/4}. \tag{6}$$

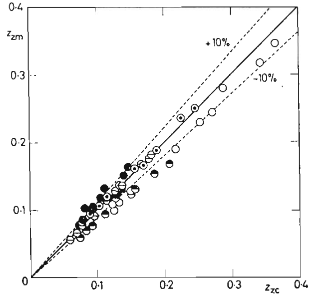

FIG. 7

Comparison of the Calculated (Eq. (7)) and Experimental Liquid Holdup at Flooding for Packing of Raschig Rings

○ Average 8 mm, ⊙ 15 mm, ◓ 20 mm, ⊖ 25 mm, ● 35 mm.

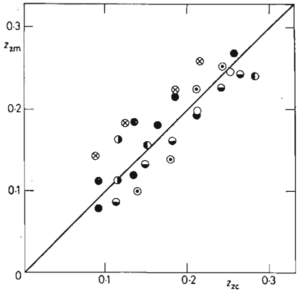

FIG. 8

Comparison of Calculated (Eq. (7)) and Experimental Liquid Holdup at Flooding for Packing of Raschig Rings of Different Authors

Porcelain *d* 6·4 mm, water–air[9] ⊙; polyethylene *d* 22 mm, water–air[9] ⊗; wettable porcelain[9] *d* 10·3, water–air ◒; saccharose–air ○; 2-propanol–air ◐; unwettable porcelain *d* 10·3, water–air[9] ◑; wettable porcelain *d* 10·3, water–air[8] ●.

If for η from Eq. (*1*) at flooding is substituted into Eq. (*6*) and if ϑ is expressed by use of the extrapolated liquid holdup z_e from Eq.(*3*) we obtain a simple relation for liquid holdup at the flooding point in the form

$$z_z = (z_e^3 e)^{1/4} . \quad (7)$$

The calculated values of liquid holdup at flooding in Figs 2–4 (large circles) are also plotted for individual packing dimensions and shapes. The agreement of experimental and calculated liquid holdups at flooding of our own data and those of other authors[8,10] is from Figs 7, 8 obviously good if we take into account that the dependence of liquid holdup is very sensitive in this region with approaching the flooding point. For a similar consideration of packed spheres follows that especially at low liquid flow rates the measured liquid holdup on the packing of spheres is lower than the calculated one. This corresponds to the explanations given earlier, according to which entrainment takes place with this packing at low liquid flow rates with liquid drops carried away from the upper layer of the packing which is the actual reason for premature stop of the experimental measurements. The empirical relation for liquid holdup at flooding published earlier[6] $z_z = 1{\cdot}177(\pm 0{\cdot}046)\, z_0$ is for experimental data with a packing of spheres more accurate than relation (*7*) but it is not valid for other types of packings as it does not include the porosity e which is expressively different with other packings. With the packing Hyperfil of large porosity the liquid holdup at the flooding point at low gas flow rates is larger than the calculated one (Fig. 4). At these liquid flow rates a consecutive flooding of the packing from the bottom took place which was not possible to prevent even by removing the grid plate. The consequences of this phenomenon are discussed later with verification of the relation for pressure drop of the packing.

In relations for calculations of liquid holdup at loading z_k (Eq. (*2*)), the extrapolated liquid holdups z_e (Eq. (*4*)), and thus also liquid holdups at flooding z_z (Eq. (*6*)) appears the liquid holdup at zero gas flow rates (mostly at zero pressure drop as well) across the bed z_0. In the last paper[6] was obtained for liquid holdup z_0 in the packed bed of glass spheres an empirical relation

$$z_0 = 0{\cdot}2654(\sigma_l/\sigma_w)^{0{\cdot}1} - 0{\cdot}2215 G_{gz}^{1/4} . \quad (8)$$

This relation has a certain rational basis in the relation which can be obtained by deriving the relation for the state at flooding

$$z_z = e - \left(\frac{\eta G_{gz}^2}{2 g \varrho_l \varrho_{gz} d_e e^3}\right)^{1/4} . \quad (9)$$

Since with the packing of Raschig rings was studied only the system water–air the suitability of the relation of Gelbe was tested[11]. This relation was presented for calculation of liquid holdup z_0 on the packing of Raschig rings. Our data in comparison with those calculated from equation of Gelbe[11] are in average for liquid holdup z_0 larger by 5 – 10% which may be the result of flooding the packed bed before the measurements. It is probable that correlation of liquid holdup z_0 in the form of Gelbe equation may be extended also to packings of other geometrical shapes of course with different empirical coefficients. A certain disadvantage presents the fact that the effect of surface quality of the material *i.e.* the effect of contact angle is not taken into consideration.

Gas Flow Rate at Flooding

Equation (*6*) presents a theoretically justified relation for calculation of gas flow rate at flooding if the coefficients η and ϑ for the given packing, liquid and gas flow rates and their physical properties are known. With Eq. (*6*) written in the form

$$\left(\frac{\eta G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{1/4} + \left(\frac{\vartheta G_l^2}{2g\varrho_l^2 d_e e^3}\right)^{1/4} = 1 \qquad (10)$$

and with the linear regression of experimental data, relations for individual packings are:

for *Raschig rings*

$$\left(\frac{\eta G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{1/4} + (1{\cdot}045 \pm 0{\cdot}0196)\left(\frac{\vartheta G_l^2}{2g\varrho_l^2 d_e e^3}\right)^{1/4} = 1{\cdot}004\,, \qquad (11a)$$

with the coefficient of correlation 0·992 for 52 measurements; for the *Hyperfil packing*

$$\left(\frac{\eta G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{1/4} + (0{\cdot}9635 + 0{\cdot}0158)\left(\frac{\vartheta G_l^2}{2g\varrho_l^2 d_e e^3}\right)^{1/4} = 0{\cdot}9581\,, \qquad (11b)$$

with the correlation coefficient 0·999 for 10 measurements. Values of regression coefficients which are close to one, and large correlation coefficients confirm that relations (*6*) and (*10*) are valid very exactly.

The majority of published correlations of the flooding point use criteria given in Eq. (*6*) or (*10*) in a graphical or analytical form, but without coefficients ϑ and η. The consequences of not including these coefficients are demonstrated on the relation of Zenz and Lavin[10] (Eq. (*12*)

$$14{\cdot}22\left(\frac{G_{gz}^2\mu_l^{0\cdot2}}{\varrho_l\varrho_{gz}d_e e^3}\right)^{1/6} + 10{\cdot}43\left(\frac{G_l^2\mu_l^{0\cdot2}}{\varrho_l^2 d_e e^3}\right)^{1/4} = 18{\cdot}9 \qquad (12)$$

which is considered to be a generalized correlation relation for the gas flow rate at flooding.

This equation is, with the exception of coefficients ϑ and η, with the exponent 1/6 of the first term for the gas flow rate, and with the included viscosity effect, analogous to Eq. (*10*). We are looking for the correlation relation for the coefficient η so that it could be substituted into the first term of Eq. (*10*) for comparison with the corresponding term of Eq. (*12*) of Zenz and Lavin.

The correlation of coefficient η was made for 5 sizes of Raschig rings both individually and together with the packing of glass spheres first for the water–air system with the aim to determine the effect of gas flow rate at flooding and the geometrical characteristics of packing. The coefficient η is correlated in the form of a correlation relation

$$\eta = AG_{gz}^{B}d_{e}^{C}e^{D}(d_{i}/d_{j})^{E}\,. \tag{13}$$

It is necessary to emphasize, that by the type of relation (*13*) the greatest part of variability of η can be expressed with a high accuracy. For the packing of Raschig rings was found a considerable effect of the internal and external ring diameters and an insignificant effect of the equivalent dimension and of porosity. On the contrary with a combined evaluation of data of glass spheres ($d_i/d_j = 1$) was found a profound effect of d_e and e and completely negligible effect of d_i/d_j. These different exponents of geometrical characteristics of packings at evaluation of Raschig rings only on at their evaluation together with a packing of glass spheres are not very surprising as with Raschig rings porosity and ratio d_i/d_j were not varied in a sufficiently wide range, which moreover are not quite independent. If we accept that the common relation for both the Raschig rings and spheres is expressing the dependence of coefficient η on geometrical characteristics of the packing for the system water–air with a sufficient accuracy ($A = 11\,482$, $B = 1{\cdot}2 \pm 0{\cdot}016$, $C = 1{\cdot}05 \pm 0{\cdot}036$, $D = 3{\cdot}038 \pm 0{\cdot}204$) and if the exponents of the effect of d_e and e are rounded off by a repeated evaluation of experiments in all the physical systems, the correlation relation for the coefficient η was obtained in the form

$$\eta G_{gz}^{1\cdot20}/d_e e^3 = 0{\cdot}03155\sigma_l^{-0\cdot684\pm0\cdot064}\varrho_l^{1\cdot54\pm0\cdot26}\mu_l^{-0\cdot017\pm0\cdot022}\,. \tag{14}$$

A low value of the exponent with the liquid viscosity and relatively high values of exponents with density and surface tension are surprising. But at this point it is necessary to stress again the presence of air in aqueous solutions of glycerol of various viscosities which could have altered physical properties of liquids and thus of the given coefficients as well, especially in the region close to the flooding point. It was not possible to correlate the coefficients of the Hyperfil packing together with the other packings and thus a separate relation was determined (for system water–air) according to which

$$\eta = 1{\cdot}972G_{gz}^{-1\cdot294\pm0\cdot065} \tag{15}$$

with the correlation coefficient 0·99 and the mean quadratic relative deviation 37·6% for 10 measurements. As the correlation of Zenz and Lavin of flooding points was based on experimental data of packing of Raschig rings, for comparison of first terms of Eqs (*10*) and (*12*) is used the relation that we have obtained by the statistical analysis for coefficient for packings of Raschig rings ($A = 474{\cdot}3$, $B = 1{\cdot}16 \pm 0{\cdot}025$, $C = 0{\cdot}292 \pm 0{\cdot}115$, $E = 5{\cdot}55 \pm 0{\cdot}6$). For the first term of Eq. (*10*) is then obtained the relation

$$\left(\frac{\eta G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{1/4} = \left[\frac{474{\cdot}3(d_i/d_j)^{5\cdot6}}{2g\varrho_l\varrho_{gz}d_e^{0\cdot71}e^3}\right]G_{gz}^{0\cdot21}\,. \tag{16}$$

From this equation is obvious, that the exponent with the gas flow rate in the first term of Eq. (*10*) equals to 0·21. Zenz and Lavin are giving in Eq. (*12*) the value of this exponent as 0·33.

The second term of Eq. (*12*) with the exponent of liquid flow rate 0·5 was obtained by Zenz and Lavin[10] at very high liquid flow rates when the flooding took place due to liquid flow only. From the dependence of coefficient ϑ on the liquid flow rate (Fig. 9) is obvious that the given exponent 0·5 is valid more as an extrapolation only at these high, and thus rarely used, liquid flow rates. While the coefficient ϑ at high liquid flow rates is almost independent on the liquid flow rate, exponent of its dependence has the value about $-1·6$ at low liquid flow rates. Thus, with in the range from the lowest up to the highest liquid flow rates, the exponent with the liquid flow rate in the second term of Eqs (*10*) and (*12*) varies from 0·1 to 0·5. Therefore use of the constant value of the exponent with the second term in Eq. (*12*) in the whole range of liquid flow rates leads to a worse agreement of experimental data with the correlation relation.

For sufficiently accurate calculation of the gas flow rate at flooding it is necessary to determine at first the coefficients ϑ and η. For packings of Raschig rings and glass spheres it is possible to determine the coefficient ϑ from the known liquid holdup z_0 of Eqs (*3*) and (*4*), the coefficient η from Eq. (*14*). But it must be mentioned, that in the case of correlation relation for coefficient η the physical properties of the studied systems with the packing of Raschig rings were not altered for evaluation of experimental data.

Pressure Drop

Pressure drop of a packed bed was expressed earlier[5] by relation

$$\Delta P_g/l = \varrho_1 g \varphi - \psi_1 G_1^2/2\varrho_1 d_e z^3 \,, \tag{17}$$

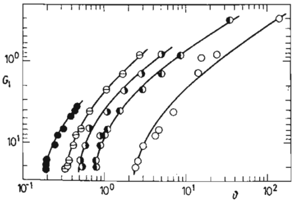

FIG. 9

Dependence of Coefficient ϑ on Liquid Flow Rate G_1 for Packing of Raschig Rings

○ d 8 mm, ◐ 15 mm, ◑ 20 mm, ⊖ 25 mm, ● 35 mm.

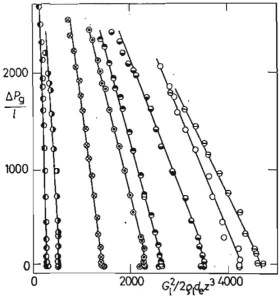

FIG. 10

Dependence of Pressure Drop of Packed Bed of Raschig Rings of d 8 mm on Gas Flow Rate in Variables of Eq. (*15*)

◐ G_1 ($kg m^{-2} s^{-1}$) = 0·833, ◑ 1·38, ⊗ 4·12, ⊙ 6·87, ◓ 8·25, ◒ 11·0, ○ 16·8, ⊖ 19·9.

where coefficient φ represents part of the liquid holdup resulting from the action of pressure and friction forces of gas and liquid and the coefficient ψ_1 represents the friction of the liquid stream with the wall and with the gaseous stream. The dependence (*17*) for the packing of Raschig rings of 8 mm diameter and for the wire packing Hyperfil is given in Figs 10 and 11. From Fig. 10 is obvious that the dependence of pressure drop of Raschig rings in the given coordinates is linear. Certain deviation from this linearity is evident only for low gas flow rates and thus at low pressure drop 200–300 Nm^{-3}. By extrapolating the dependence of pressure drop from high values to its zero value the liquid holdup is obtained which is only by several percent less than the experimentally determined one. An exact investigation was difficult due to small expressiveness of points where the change of slopes takes place as the differences in liquid holdups were already in the range of accuracy in the holdup measurements.

The systematic way in the slope change leads to its possible interpretation based on the way the packing is wetted before the beginning of the measurement. As has been already mentioned, the bed was wetted by its flooding at a fixed liquid flow rate for 15 min. The gas flow was then stopped, a break of 15–20 min was made and the measurement was carried out with successively increasing gas flow rate. The packed bed after flooding holds, perhaps due to surface forces, more liquid than it would correspond to the dynamic equilibrium of forces. The increase of gas flow rate leads to dynamic action on menisci which successively allow the excessive liquid to leave in certain locations of the bed and thus the increase in liquid holdup is slower than would correspond to the slope of dependence in the region of higher pressure drops. Above mentioned

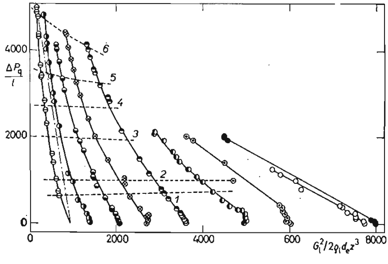

FIG. 11

Dependence of Pressure Drop of Bed of Hyperfil Packing on Gas Flow Rate in Variables of Eq. (*15*)

⊖ G_l (kgm^{-2} s^{-1}) = 5·51, ◑ 8·52, ◒ 12·5, ⊗ 16·9, ◓ 21·6, ◐ 29·0, ⊙ 36·5, ○ 49·2, ● 61·6. Dotted lines represent fraction of height of flooded packing x: *1* 0·05, *2* 0·1, *3* 0·3, *4* 0·5, *5* 0·7, *6* 10. Dashed and dotted line represents the straight connecting line of zero pressure drop and pressure drop at flooding for G_l = 5·51 kg m^{-2} s^{-1}.

character of pressure drop dependence is typical for all measured types of packings. With some dimensions the break in slope is more or less expressive. But none unique rule has been found so far.

Quite different character has the dependence of pressure drop for the wire packing Hyperfil at — due to large porosity — low liquid flow rates. With these flow rates a successive flooding of the packing from the bottom took place. The height of the bed flooded from the bottom was at low liquid flow rates relatively constants, the change between the flooded and not flooded packed bed was sufficiently expressive. The upper, not flooded, part of the packing was in the state close to the loading point. With increase of the gas flow rate the flooded part of the packing was increasing. We supposed that the flooding from the bottom was the result of the effect of the grid as all the considered packings were flooded regularly in the whole bed height of the packing above which a liquid layer has formed accompanied by a large entrainment of liquid droplets. But after the removal of the grid this state has not changed and thus we consider this phenomena to be a property of this type of packing. By observing the liquid drainage from the lower end of the vertical plate at countercurrent gas flow in the flooding region it has been determined that for continuous formation of liquid droplets it is necessary to accumulate a certain amount of liquid to overcome pressure forces of the gas and forces of surface tension of liquid. This local increase of liquid holdup which takes place also in the packing Hyperfil is causing decrease of the area for passage of gas and causes flooding at the bottom part of the packing which at the increasing gas flow rate moves upward. We have made an effort to improve conditions for liquid drainage by situating 110 wires of 0·4 mm diameter and 40 mm length into the bottom part of the packed bed. Although by using these wires the local porosity of the bed was reduced, the gas flow rates at the beginning and at complete flooding were higher by 11·5%. The successive flooding of the bed has not thus been eliminated but it begins at higher gas flow rates. Also the shape of dependence of pressure drop on gas velocity (Fig. 11) was not affected. It is possible to state, that beds, having a grid of low porosity or where liquid drainage is not good, will be flooded from the bottom at lower gas flow rates than necessary.

The curved dependences of gas pressure drop for the packing Hyperfil as given in Fig. 11 can be straightened by use of a suitably chosen coordinate which takes into account the successive flooding of the packing from the bottom. Let us assume that the part of bed height x is flooded from the bottom and that it has a liquid holdup z_z, with the remaining bed height $(1 - x)$ corresponding to the looding point with the liquid holdup z_k. The over-all pressure drop across the bed is written

$$\Delta P_g/_1 = x(\Delta P_g/l)_z + (1 - x)(\Delta P_g/_1)_k \,. \tag{18}$$

It can be assumed that the coefficients φ and ψ_l have about a constant value because the liquid flow rates through the bed at flooding and at loading are equal and thus it may be written

$$\Delta P_g/l = \varrho_l g \varphi - \frac{\psi_l G_l^2}{2\varrho_l d_e}\left[\frac{x}{z_z^3} + \frac{1 - x}{z_k^3}\right]. \tag{19}$$

Eq. (19) gives a coordinate for which the dependence of pressure drop should be straight. In Fig. 11 are plotted experimental values of pressure drop with the coordinate calculated from the experimental mean liquid holdup across the whole packed bed and thus the curved character of this dependence has its foundation. In Fig. 11, straight connecting line may be constructed between the pressure drop at flooding of the whole packed bed ($x = 1$) and the zero pressure drop ($x = 0$) for which the coordinates are correct and then for different relative flooded packed bed heights x is read off the value of the coordinate and compared with that one calculated from Eq. (*19*). A comparison made this way with the coordinates calculated from the averaged liquid holdups is good. For calculation of pressure drop the same procedure published recently[7] can be applied. For the ratio of pressure drops can be written relation

$$\frac{\Delta P_g}{\Delta P_{gz}} = \frac{z^3 - z_0^3 \, \frac{z_z^3}{z^3}}{z_z^3 - z_0^3 \, \frac{z_z^3}{z^3}}, \tag{20}$$

and for pressure drop at flooding ΔP_{gz} relation

$$\Delta P_{gz} = \psi_{gz}(l/d_e) \, G_{gz}^2/2\varrho_{gz}d_e(e - z_z)^3 \,. \tag{21}$$

The friction factor for gas at flooding ψ_{gz} is correlated in the same way as earlier[7]: for the packing of *Raschig rings*

$$\frac{\psi_{gz}}{\psi_{gs}} = 0.4575 \left(\frac{G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{-0.6016}, \tag{22}$$

with the mean relative deviation 9.5% and with the correlation coefficient 0.992 from 52 measurements, for packing *Hyperfil*

$$\psi_{gz} = 0.4575 \left(\frac{G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{-0.626 \pm 0.035}, \tag{23}$$

with the mean quadratic relative deviation 40% and with the correlation coefficient 0.992 from 10 measurements. For the packing of *glass spheres* has been earlier determined the relation

$$\frac{\psi_{gz}}{\psi_{gs}} = 0.48 \left(\frac{G_{gz}^2}{2g\varrho_l\varrho_{gz}d_e e^3}\right)^{-0.723}. \tag{24}$$

The friction factor of the dry packed bed ψ_{gs} was for individual packing sizes expressed by use of the Ergun relation[12]

$$\psi_{gs} = A/\mathrm{Re}_g + B \,. \tag{25}$$

Coefficients A and B are given in Table II. Coefficient ψ_{gs} is calculated from Eq. (*25*) at the Reynolds number for the extrapolated gas flow rate at zero liquid flow rate $G_{gz}(G_l = 0)$ calculated from the relation for flooding Eq. (*10*).

TABLE II

Coefficients of Ergun Equation A and B for Calculation of Friction Factor of Dry Packed Bed ψ_{gs} acc. to Eq. (*25*)

Correlation coefficients: ~ 0.999.

Packing, mm	A	B	Packing, mm	A	B
Raschig rings			Raschig rings		
⌀ 8	18·3	0·868	⌀ 25	51·2	0·966
⌀ 15	28·8	1·094	⌀ 35	50·2	0·876
⌀ 20	36·4	1·026	Hyperfil	17·0	0·436
			Spheres ⌀ 10	6·29	0·265

CONCLUSIONS

The conclusions made on basis of experimental data with glass spheres representing the simplest packing shape are, after including the effect of porosity, in agreement with results obtained by evaluating experimental data on packing of Raschig rings, wire packing of large porosity Hyperfil and with data of other authors. The number of empirical relations was reduced and their accuracy was improved, but their complete elimination is very unlikely.

The formerly proposed relation for the liquid holdup in the flooding point was generalized and it was substituted by a theoretically derived relation (*7*). Also some aspects of correlation of gas flow rates at flooding were explained. Though there is not given a correlation relation for different geometrical packing shapes and different physical properties of liquids (for lack of experimental data of coefficients η and ϑ) a recommendation is given how to proceed at correlation of gas flow rates at flooding. The extrapolated liquid holdup z_e (Eq. (*4*)), liquid holdup at the loading point z_k (Eq. (*2*)) and thus also the gas flow at the loading point G_{gk} determined form Eq. (*1*) are still expressed by empirical relations. Relation for pressure drop of a bed of packing (Eq. (*17*)) is linear in a sufficiently wide range of gas flow rates. The break of slope in the graph is not very clear and it would be possible to explain it by the hysteresis but this would require additional measurements. For the packing Hyperfil in the range of loading and flooding points there was determined an irregular distribution of liquid holdup along the bed height with successive flooding from the bottom *i.e.* a certain vertical stratification whose origin and effect on relation for pressure drop we have tried to describe mathematically.

For calculation of liquid holdup and gas pressure drop for the chosen gas and liquid flow rates the knowledge of the following quantities is necessary: Liquid holdup without the gas flow rate z_0 – for example from correlation of Gelbe[11] for Raschig rings or correlation[6] for glass spheres from Eq. (*8*); coefficient η calculated from Eqs (*14*) and (*15*); coefficient of dry packed bed ψ_{gs} from Eq. (*25*). The extrapolated liquid holdup z_e is calculated from Eq. (*4*), liquid holdup at flooding from Eq. (*7*), liquid holdup at loading from Eq. (*2*), coefficient ϑ from value z_e from Eq. (*3*), the gas flow rate at flooding point from Eq. (*10*). The dependence of liquid holdup on gas flow rate in the region $G_{gk} \leqq G_g \leqq G_{gz}$ is given[6] by relation

$$\left(\frac{G_g}{G_{gz}}\right)^2 \frac{\varrho_{gz}}{\varrho_g} = \left(\frac{z^3 - z_e^3}{z_z^3 - z_e^3}\right)\left(\frac{(e - z)\, z_z}{(e - z_z)\, z}\right)^3 . \qquad (26)$$

By substituting z_k from Eq. (*2*) into relation (*26*) is obtained the gas flow rate in the loading point G_{gk}. The liquid holdup in the region $0 \leqq G_g \leqq G_{gk}$ is then calculated[6] from relation

$$\left(\frac{G_g}{G_{gk}}\right)^2 \frac{\varrho_{gk}}{\varrho_g} = \frac{z^3 - z_0^3}{z_k^3 - z_0^3}\left(\frac{(e - z)\, z_k}{(e - z_k)\, z}\right)^3 . \qquad (27)$$

The pressure drop at flooding ΔP_{gz} is calculated from Eqs (*21*) to (*25*) and in the whole range of gas flow rates by use of Eq. (*20*).

LIST OF SYMBOLS

A, B, C, D, E	constants
a	surface area of packing per unit volume of bed (m^{-1})
d	packing size, diameter of rings (mm)
$d_e = 1/a$	characteristic dimension of packing (m)
e	porosity of dry packing
g	acceleration of gravity (ms^{-2})
h	height of Raschig rings (mm)
G	mass flow rate per unit area (kg m^{-2} s^{-1})
l	bed height (m)
ΔP	pressure drop of packed bed (Nm^{-2})
$\mathrm{Re} = Gd_e/\mu$	Reynolds number
x	relative (fraction) of height of flooded packed bed
z	liquid holdup per unit volume
ϑ, η	coefficients in Eq. (*1*)
φ	fraction of liquid holdup carried by friction and pressure forces of gas and liquid
ψ	friction factor
ϱ	density (kg m^{-3})
μ	viscosity (N s m^{-2})
σ	surface tension (N m^{-1})
ξ	coefficient in Eq. (*5*)
ζ	coefficient in Eq. (*5*) (N m^{-3})

Subscripts

c calculated
e extrapolated value
g gas
i internal
j external
k loading
l liquid
m measured
o value at $G_q = 0$
s dry bed
st static
w water
z flooding

REFERENCES

1. Kolář V., Brož Z.: This Journal *30*, 2527 (1965).
2. Brož Z., Kolář V.: This Journal *33*, 349 (1968).
3. Kolář V., Brož Z.: This Journal *33*, 2722 (1968).
4. Kolář V., Tichý J.: This Journal *33*, 2728 (1968).
5. Kolář V., Brož Z.: This Journal *33*, 3870 (1968).
6. Kolář V., Brož Z., Tichý J.: This Journal *35*, 3344 (1970).
7. Kolář V., Brož Z.: This Journal *37*, 1666 (1972).
8. Musil L., Prost C., Le Goff P.: Chim. Ind. Gén. Chim. *100*, 674 (1968).
9. Charpentier J. C., Prost C., Van Swaaij W., Le Goff P.: Chim. Ind. Gén. Chim. *99*, 803 (1968).
10. Zenz F. A., Lavin R. A.: Petrol. Refiner *44*, 121 (1965).
11. Gelbe H.: Chem. Eng. Sci. *23*, 1401 (1968).
12. Ergun S., Orning A. A.: Ind. Eng. Chem. *41*, 1179 (1949).

Translated by M. Rylek.