A VERSATILE CORRELATION OF LIQUID HOLD-UP UNDER THE SINGLE-PHASE TRICKLE FLOW IN A PACKED BED

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The paper gives a review of present approaches to the problem of a single- and two-phase flow in a packed bed. A new definititon has been given of the flooding point, which, as far as the theory is concerned, rigorously defines critical values of the quantities in the flooding point. At the same time, the definition enables a unambiguous experimental determination of the flooding point from experimental dependence sof the hold-up or pressure drop on the flow rate of phases. Based on extensive experimental data three alternative forms have been proposed of the versatile correlation of liquid hold-up on the velocity of liquid at the zero velocity of gas. The correlations have been formulated on the principle of automodel properties and define the appropriate relationships in terms of normalized variables related to the newly defined flooding point. The dependences on the geometry parameters of the packing and physical properties of liquid appear in the versatile correlations only implicitly. A new possibility has been shown of inverse utilization of the versatile correlations for the determination of the critical values (the flooding point) from two independent measurements of liquid hold-up in a real apparatus.

The hydrodynamics of two-phase flow through an immobile bed of packed material is a complex phenomenon which significantly hampers a deeper knowledge of the processes of mass an heat transfer in a large variety of technological equipment.

The complexity of the hydrodynamics of two-phase flow rests in the various interactions of the phases outwardly manifested through complicated effects of the flow rates of phases, physico-chemical properties of fluids and the geometry of the system. These complexities appear both in the cocurrent as well as counter-current beds. Also a non-negligible factor is the wettability of the packing, stochastic character of the studied dependences and the hysteresis of the system[1,2].

Thus far published models of the structure of the flow through a bed of granular material start from the balance of forces[1,10-11] acting on the liquid flowing through a channel or a system of channels (straight, with constriction, *etc.*)[3-6,18], or liquid flowing down an inclined plane[13,14], or, eventually, the liquid flowing past a body[7-10].

There exist also stochastic models of the flow of liquid in a packed bed[15,16], models utilizing the theory of filtration (percolation theory)[17] or models of statistical nature.

The models are thus built on a simplified concept of the structure of the system and the phenomenon proper and remain either entirely theoretical, or, after introducing empirical constants, form basis for correlations[1,6] of the hold-up and/or pressure drop. The form of these correlations sometimes follows from the dimensional

analysis[19], or, in other cases the correlations are mere regressions of experimental dependences[20].

Generally these correlations take the form

$$h = k_1 Q^{k_2} . \qquad (1)$$

where h is the total or dynamic hold-up and the constant k_1 is a power function of the physical properties of liquid $(\varrho_1, \eta_1, \sigma_1)$ and the geometry characteristics of the packing $(\varepsilon, N, d_p/a)$. In some correlations for the two-phase flow the hold-up has been correlated with the ratio of the flow rates of phases.

The widest application and practical utilization received correlations in the form of nomograms[21,22]; use of nomograms for the design of absorption apparatuses is shown in ref.[23].

The validity of the published dependences is usually limited to a certain region of *e.g.* loading point[3,27–30,32]. There are correlations of the flooding[13,26], correlations for only liquid phase irrigating the bed[7,19,24,25,30], *etc.*

Important from practical standpoint appear correlations of the flooding phenomenon which limits the loading capacity of the bed. A review of papers dealing with the mechanism of flooding is given in refs[13,31]. While the loading point is not very conspicuous and its localizations is not unambiguous, the region of the flooding is relatively clearly cut. Even here, though, a certain degree of subjectivity remains too.

A review of experimental methods of measurement of the hold-up (static, dynamic and total) and their applicability is given in ref.[33].

The aim of this work is to find relationships between principal quantities controling the hydrodynamics of the flow in a packed bed while minimizing the degree of empiricism.

THEORETICAL

A review of the literature given in the preceding paragraph indicates that the character of the flow of phases and their interactions are so complex that a description on the basis of a physical model appears at present impissible. As difficult and, in fact, impractical thus generally appears the search for an explicit expression of the functional relationship between principal hydrodynamic quantities of the flow, *i.e.* the hold-up and pressure drop on the one hand and the process variables, such as the flow rates of phases and further physical and geometry characteristics of the system, on the other hand.

As more promising appear implicit expressions of these relations utilizing automodel properties of the system. The success or failure of this approach depends in the first place on whether the elements of the automodel properties in the system proper exist and are discovered. In principle thus we search for a point within the multidimensional space of variables and parameters, to which the measured quantities and process variables are referred. If we are successful, the result of the

transformation is a single functional relationship between transformed quantities which is invariant to the change of properties expressed in the original, non-transformed variables. This approach has met with success, for instance, in case of the generalized diagram of PVT behaviour, i.e. the theorem of corresponding states for real gases. In principle, the outlined approach has been applied to the problem of the hydrodynamics earlier by some authors[21,34].

As the reference point for the normalization of the quantities we shall use a newly defined flooding point. The earlier definitions[13,26] in the form

$$\partial Q_g/\partial h = 0 \quad \text{or} \quad \partial A_p/\partial Q_g = \infty \tag{1a}$$

are insatisfactory both on the physical and mathematical grounds. Physically because the increment of pressure losses has a finite value, even past the point of flooding given by the balance of the formed liquid head and the force effects of the flowing gas. Specific hold-up of liquid has also evidently a finite upper limit both within the packed section given by its porosity, as well as within the empty section of the column, given by unity.

From the mathematical standpoint and for the purpose of generalization of the functional relationship these definitions are also insatisfactory as they do not determine values of the hold-up and pressure drop at the flooding point.

The flooding point is newly defined as a point when first infinitesimal increments of the gas/liquid mixture appear on the top of the packed section of the column. For a given system (column, packing, liquid, gas) this definition of the flooding „point" actually fixes curves in the $h_p - Q_g - Q_l$ and $\Delta p_p - Q_g - Q_l$ space, drawn on the surfaces which in the above spaces determine the functional relationships between these quantities. The quantities falling onto the lines of flooding shall be designated by the subscript „f" and if we confine ourselves to the case of a single-phase flow of liquid ($Q_g = 0$) the surface in the above mentioned spaces reduces, in the particular case of hold-up, to

$$h_p = f(Q_l) \tag{2}$$

and the flooding line actually reduces to a point (σ_{pf}, Q_{lf}).

In the part experimental we shall test on a extensive experimental material whether the system exhibits, with respect to this newly defined flooding, the automodel properties, *i.e.* whether the functional relationship

$$\bar{h}_p = g(\bar{Q}_l), \tag{3}$$

where

$$\bar{h}_p = h_p/h_{pf} \tag{4}$$

$$\bar{Q}_l = Q_l/Q_{lf} \tag{5}$$

is invariant to the variations of the properties of the system. In other words we shall examine whether different systems behave identically if they appear in the same relative distance from the newly defined flooding point.

EXPERIMENTAL

The apparatus is of usual construction for the measurement of the hold-up by weighing[1,2,29,35], with the difference that the column is suspended on a tensometric balance. The experiments were carried out with a column 190 mm in internal diameter packed to a height of 1 m. The packings used were glass spheres 10, 15 and 20 mm in diameter ($\varepsilon = 0{\cdot}392$) and 15 mm ceramic Raschig rings ($\varepsilon = 0{\cdot}698$).

The mass of the column and its variations were determined by weighing the column under the operating conditions. The dynamic properties of the tensometric balance enable measurements of the hold-up both in the steady as well as the transient state. The design of the balance permits measurements in columns of the total weight up to 200 kg with an accuracy of the hold-up of 1‰. With the packed height of 1 m the upper limit of the loading capacity of the balance corresponds to a column about 0·5 m in diameter.

Hold-up. The applied experimental technique enables determination of two or three kinds of hold-ups (Fig. 1). The total hold-up, which, in this paper, designates all hold-up in the column, *i.e.* within the packed section (bed) and in the gas/liquid mixture on top of the packed section (existing only under intensive regimes given by high flow rates of phases). The value of thus defined hold-up follows from directly measured quantities, namely from the difference of the total mass of the column and the total pressure drop across the column, Δp_t:

$$h_t = \frac{1}{\varrho_l V_p}(G_{hl} - G_0) + \Delta p_t S_B / g \,. \qquad (6)$$

Further we can determine the hold-up within the packed section alone, h_p. For its determination one needs, in addition, data on the hydrostatic pressure of the gas/liquid mixture on top of the

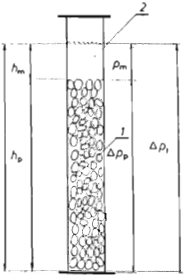

FIG. 1

Scheme of measured hold-ups and pressure drops. *1* packed section, *2* gas/liquid mixture

packed section, Δp_m:

$$h_p = h_t - \Delta p_m \frac{S_C}{\varrho_l V_p g} = h_t - h_m . \qquad (7)$$

This pressure was measured by means of a pressure transducer of the same type as that used for the total pressure drop. Finally, we can measure the hold-up of liquid in the gas/liquid mixture, h_m, given by the second term on the right hand side of Eq. (7).

The pressure drop across the whole column was measured by a capacity transducer DISA of the 51D02 type. This measurement is indispensable also for the calculation of the real mass of the column under the operating conditions from the data of the tensometric balance. In accord with Fig. 1 the total pressure drop, Δp_t,(measured by a transducer), equals the sum of the pressure drop across the packed section, Δp_p, and across the gas/ liquid mixture, Δp_m, appearing on top of the packed section under intensive regimes of operation (measured by another transducer):

$$\Delta p_t = \Delta p_p + \Delta p_m \qquad (8)$$

Physical properties of five liquids used are summarized in Table I. In the course of measurements the liquid was thermostated to $20 \pm 0{\cdot}5°C$. Physico-chemical properties of the liquid were regularly checked; density by pycnometry, viscosity by the Hoepler viscometer, surface tension by the method of weighted droplets. A review of the various combinations of packings and liquids in individual experimental runs is given in Table II.

RESULTS

Typical courses of the hold-up and pressure drop are given in Figs 2–5 in the form of dependences on the flow rate of liquid and gas. Presentation in the form of the dependence on the gas flow rate is more common in the literature, while the main and probably the only reason for this is that the data for this form of graphical presentation are directly obtained from two-phase flow experiments. The trends of our experimental data in these plots are in agreement with similar published measurements[1,2,38].

TABLE I
Physical properties of liquids used

Liquid 20°C	ϱ kg/m^3	η_l mPa . s	σ_l mN/m
Water	998·23	1·005	72·9
Saturated water solution of isobutanol	988·2–989·2	1·20–1·28	27·93–30·81
Water solution of $CaCl_2$	1 259·8–1 262·9	3·40–3·54	68·04–76·9
Technical grade glycerol	1 110·4–1 116·5	5·22–5·72	39·17
Cosmetics grade glycerol	1 049·5–1 050·2	2·04–2·14	70·04–71·6

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TABLE II

Coefficients of regressions (*9*), (*10*) and (*11*)

Regression	Eq. (*9*)				Eq. (*10*)		Eq. (*11*)				
Liquid	A	B	k_r	δ	A'	δ	B'	C	D	k_r	δ
Water	0·2074	0·7597	0·993	0·02399	0·8129	0·02919	0·1793	0·5492	0·4612	0·995	0·02982
Water solution of isobutanol	0·1072	0·9158	0·993	0·03078	0·8784	0·03255	0·1148	−0·3518	0·3477	0·994	0·02823
Technical grade glycerol	0·2106	0·7719	0·996	0·01819	0·8025	0·01998	0·1302	0·8802	0·7217	0·999	0·00804
Water solution of $CaCl_2$	0·2361	0·7680	0·999	0·005189	0·7612	0·00541	0·2776	0·1050	1·0636	0·999	0·00453
Cosmetics grade glycerol	0·19302	0·8101	0·998	0·01906	0·8059	0·01848	0·1750	0·2418	0·7744	0·998	0·01848
All summarily	0·18651	0·8000	0·991	0·03090	0·8216	0·03153	0·1656	0·3024	0·5602	0·996	0·0319

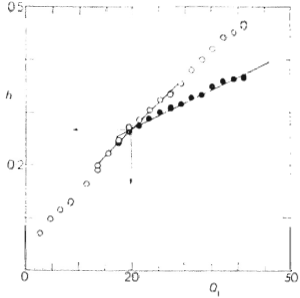

FIG. 2

Liquid hold-up as a function liquid velocity, saturated water solution of isobutanol, 10 mm spheres. ○ total hold-up in column, h_t; ● hold-up in packed section only, h_p

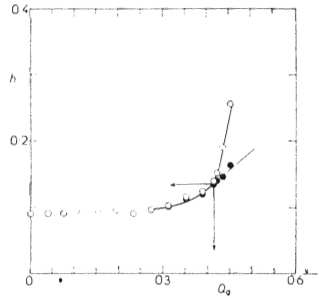

FIG. 3

Liquid hold-up as a function of gas velocity, technical grade glycerol, air, 10 mm spheres. ○ total hold-up in column, h_t; ● hold-up in packed section only, h_p

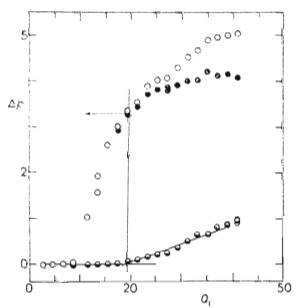

FIG. 4

Pressure drop as a function of liquid velocity, saturated water solution of isobutanol, 10 mm spheres. ○ total pressure drop across the whole column, Δp_t; ● pressure drop across packed section, Δp_p; ◒ pressure drop across gas/liquid mixture, Δp_m

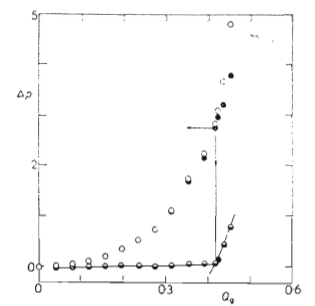

FIG. 5

Pressure drop as a function of gas velocity, technical grade glycerol, air, 10 mm spheres. ○ pressure drop across the whole column, Δp_t; ● pressure drop across the packed section, Δp_p; ◒ pressure drop across the gas/liquid mixture, Δp_m

A quantitative comparison with existing correlations[3,7,19,25,30] has been published earlier[36,37].

Figs 2–5 show graphically two of the three hold-ups and all three pressure drops defined in this work, while the total hold-up and the hold-up in the packed section alone (analogously also for the pressure drop) are graphically distinguished with the explanation in the captions of these figures. From the experiments it is apparent that for low intensity regimes, when there is still no gas/liquid mixture formed on top of the packed section, the results of the total hold-up, h_t, and the hold-up in the packed section alone, h_p, are identical within an experimental error. The same applies to the pressure drops Δp_t and Δp_p. The point where the courses of these quantities begin to depart has been defined in the part theoretical as the flooding point. The determination of this point was performed, on the one hand, graphically (see Figs 2–5) and, on the other hand, the procedure was algoritmized for a routine evaluation on a computer. As most convenient appears the determination of the flooding point from the course of the pressure drop across the gas/liquid mixture, Δp_m, see Figs 4 and 5. From Figs 2–5 it is apparent that the new definition of the flooding point well and unambiguously defines the coordinates of the flooding point, *i.e.* the hold-up, the pressure drop and the flow rates (h_{pf}, Δ_{pf}, Q_{lf}, Q_{gf}).

It should be noted that even in the case of the single-phase flow ($Q_g = 0$), which is in the focus of this communication, measureable „pressure drops" of gas appear in the bed as a consequence of the pumping effect of the flowing liquid under the intensive regimes of irrigation. This situation is illustrated in Fig. 4. Thus in this case too the routine of detection and evaluation of the flooding point remains without a change.

TABLE III

A review of the combinations of liquids and packings used in the experiments

Liquid	Glass spheres, diameter in mm			Raschig rings
	10	15	20	15 × 15 mm
Water	+	+	+	+
Water solution of isobutanol	+	+	+	–
Water solution of $CaCl_2$	+	–	–	–
Technical grade glycerol	–	–	+	–
Cosmetics grade glycerol	+	–	–	–

The evaluated quantities h_{pf}, Q_{1f}, were used in turn to evaluate the reduced quantities $\bar{h}_p$, $\bar{Q}_1$ from Eq. (*4*), because further processing, aimed at utilizing the automodel properties, concentrated in this work on the region of the single-phase flow of liquid.

The resulting dependences of the reduced hold-up on the reduced flow rate of liquid are shown in Figs 6–10 for various liquids and packings. The course of the obtained dependences is approximately linear. Parameters of a general straight line

$$\bar{h}_p = A\bar{Q}_1 + B \tag{9}$$

for the region up to the flooding point, *i.e.* up to $\bar{h}_p = 1$ and $\bar{Q}_1$ are summarized together with the standard deviation and the correlation coefficient in Table III. Because, however, the appropriate reduced dependences must pass through the point (1,1) in the $(\bar{h}_p, \bar{Q}_1)$ plane, the following one-parameter straight line, automatically satisfying this condition, was fitted to the same set of data

$$\bar{h}_p = A'(\bar{Q}_1 - 1) + 1 . \tag{10}$$

The correlation coefficient of this dependence is necessarily the same as for the previous case and the sum of the parameters $(A + B)$ for the general straight line differs

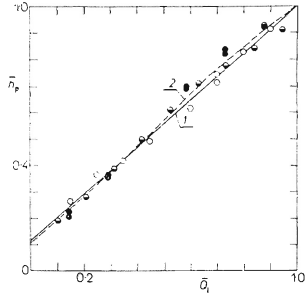

FIG. 6

Plot of normalized hold-up *versus* normalized velocity. Water, ○ 10 mm spheres, ● 15 mm spheres, ◒ 20 mm spheres, ◓ 15 × 15 mm Raschig rings. *1* Solid line given by Eq. (*10*); *2* broken line given by Eq. (*11*)

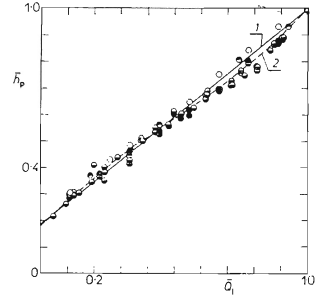

FIG. 7

Plot of normalized hold-up *versus* normalized liquid velocity. Saturated water solution of isobutanol, ○ 10 mm spheres, ● 15 mm spheres, ◓ 20 mm spheres. *1* Solid line given by Eq. (*10*), *2* broken line given by Eq. (*11*)

from unity within the standard deviation of the measurement. Values of the parameter A' are shown in Table III.

The scatter of the experimental data points in terms of the reduced variables about the above straight lines shows, for instance, for the case of water, systematic positive deviations for the reduced flow rates less than approximately 0·5. On the contrary, for the flow rates over 0·5 corresponding deviations are mostly negative. This S-shaped course of the dependence was fitted by an empirical correlation in the form

$$\bar{h}_p = B' + (1 - B')\,\bar{Q}_1 + C(\bar{Q}_1 - D)(\bar{Q}_1 - 1)\,\bar{Q}_1 . \qquad (11)$$

This curve, similarly as the straight line (*10*), passes exactly through the flooding point, *i.e.* in the reduced variables through the point (1,1) and intersects the straight line (*10*) at the point $\bar{Q}_1 = D$. Values of the parameters of the curve (*11*) are given also in Table III. The course of corresponding curves is shown also in Figs 6–11.

Versatile values of the constant for all three types of the reduced dependences (*9*), (*10*), (*11*) were evaluated by processing summarily all experimental data. Numerical values are shown in Table III in its last line. The high value of the correlation coefficient indicates a good agreement and the soundness of the employed automodel property concept. Figs 12–14 show the dependences (*9*), (*10*), (*11*) computed from all experimental data.

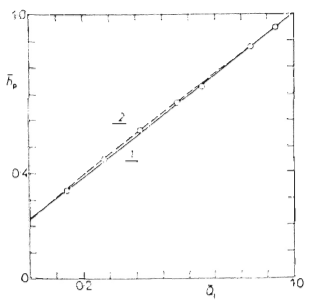

FIG. 8

Plot of normalized hold-up *versus* normalized liquid velocity. Water solution of $CaCl_2$, ○ 10 mm spheres. *1* Solid line given by Eq. (*10*); 2 broken line given by Eq. (*11*)

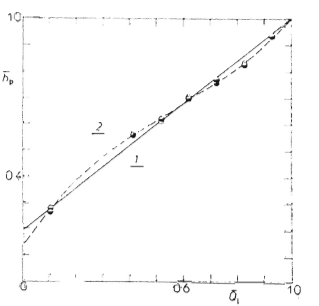

FIG. 9

Plot of normalized hold-up *versus* normalized liquid velocity. Technical grade glycerol, ◒ 20 mm spheres. *1* Solid line given by Eq. (*10*), 2 broken line given by Eq. (*11*)

CONCLUSION

The earlier developed and described[36] tensometric method of weighing the column under the operating conditions has been utilized for the determination of the hold-up and pressure drop in an irrigated column for five different liquids, two types of packings and three different sizes. A new definition of the flooding point has been proposed, which unambiguously determines critical values of all variables at the flooding point. The employed experimental technique enables these values to be evaluated reliably and, in fact, permits measurements in region past the flooding point

The new definition of the flooding point was employed to test the automodel behaviour (properties) of the investigated system, initially for the single phase flow region. Versatile values of parameters were determined of one up to three parameter dependences of the reduced hold-up of liquid, related to the packed section only, on the reduced velocity of liquid. Standard deviations of these versatile correlations amount to about 3% of the hold-up at the flooding point.

Utilization of the versatile correlations for practical calculations of the hold-up has been so far limited by the availability of the quantities h_{pf}, Q_{lf}, which must be known for the reverse transformation of the reduced quantities to dimensional data.

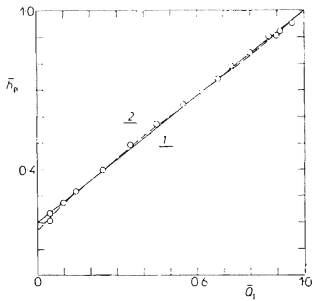

FIG. 10

Plot of normalized hold-up *versus* normalized liquid velocity. Technical grade glycerol, ○ 10 mm spheres. *1* Solid line given by Eq. (*10*), 2 broken line given by Eq. (*11*)

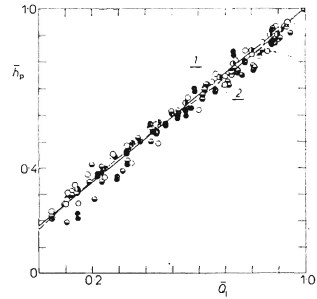

FIG. 11

Plot of normalized hold-up *versus* normalized liquid velocity for all liquids and packings investigated. ○ Water, ● saturated water solution of isobutanol, ◒ water solution of $CaCl_2$, ◓ technical grade glycerol, ◑ cosmetics grade glycerol. *1* Solid line given by Eq. (*10*), 2 broken line given by Eq. (*11*)

The correlation of the quantities characterizing the flooding point in dependence on physical properties and the geometry of the system is subject of further study. Already at this stage, however, the presented generalized relationships can be used inversely for the determination of the hold-up and liquid velocity h_{lf}, Q_{1f} from two

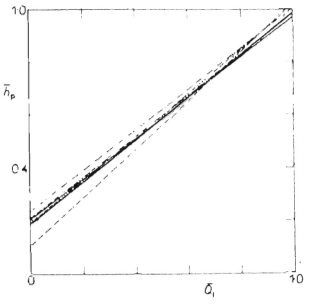

FIG. 12

Normalized hold-up as a function of normalized liquid velocity according Eq. (*9*). ——— Water, – – – – – saturated water solution of isobutanol, –·–·– water solution of $CaCl_2$, – – ·– – technical grade glycerol, ·····cosmetics grade glycerol, ——— versatile for all liquids investigated

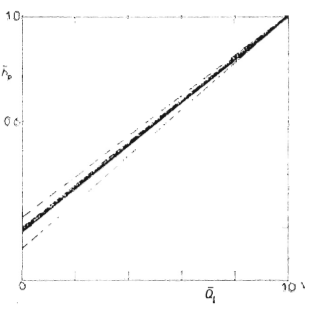

FIG. 13

Normalized hold-up as a function of normalized liquid velocity according to Eq. (*10*). ——— Water, – – – – – saturated water solution of isobutanol –·–·– water solution of $CaCl_2$, – – ·– – technical grade glycerol, ·····cosmetics grade glycerol, ——— versatile for all liquids investigated

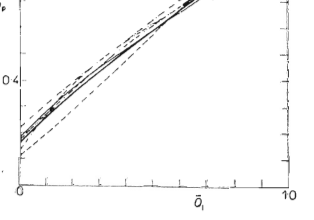

FIG. 14

Normalized hold-up as a function of normalized liquid velocity according to Eq. (*11*). ——— Water, – – – – – saturated water solution of isobutanol, –·–·– water solution of $CaCl_2$, – – ·– – technical grade glycerol, ·····cosmetics grade glycerol, ——— versatile for all liquids investigated

known values of the hold-up and liquid velocity (h_{p1}, Q_{11}), (h_{p2}, Q_{12}). Substitution of these data into some of the generalized correlations (*9*)–(*11*), with the values of the constants from Table III, yields two equations for two unknowns h_{pf}, Q_{1f}. Because liquid hold-up can be determined even in an equipment of industrial size with sufficient accuracy by an independent technique (*e.g.* the tracer technique) without undue technical difficulty, the proposed method appers as an effective means of determining the characteristics of flooding in large-scale packed systems.

LIST OF SYMBOLS

a	specific surface of packing m^2/m^3
A, B	constants in Eq. (*9*)
A'	constant in Eq. (*10*)
B'	constant in Eq. (*11*)
d_p	characteristic dimension of packing
g	acceleration due to gravity m/s^2
C_M	mass of bed under operating conditions kg
C_0	mass of dry bed kg
hl	total hold-up
h_p	hold-up in packed section only
h_{pf}	hold-up in packed section in the flooding point
$\bar{h}_p$	normalized hold-up in packed section only defined by Eq. (*5*)
k_r	correlation coefficient
N	number of packing pieces
Q_{1f}	superficial liquid mass velocity in the flooding point kg/m^2s
$\bar{Q}_1$	normalized liquid velocity defined by Eq. (*5*)
Q_g	superficial gas mass velocity kg/m^2s
Q_1	superficial liquid mass velocity kg/m^2s
S_C	internal column cross sectional area
S_B	internal cross sectional area of the bell
V_p	volume of packing m^3
ϱ_1	liquid density kg/m^3
ν_1	liquid viscosity kg/ms^2
σ_1	surface tension of liquid N/m
ε	porosity
δ	standard deviation

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