HOLDUP AND HOLDUP PROFILES IN THE RECIPROCATING PLATE EXTRACTOR VPE

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In this work measurements of mean holdup of dispersed phase, of axial holdup profiles and of flooding points in a reciprocating plate contactor with both the VPE-type plates and the sieve plates were carried out. The experimental results were compared with a monodisperse model of steady-state column hydrodynamics and the model parameters were evaluated. Important differences in the behaviour of the two plate types could be identified. Comparison was also made between two reciprocating drives of different pulse form.

EXPERIMENTAL

The experiments were carried out in a glass column of 8·5 cm I.D. and 4·1 m length (Fig. 1). Five sampling valves were located in the distances 0·6; 1·2; 2·4; 2·9 and 3·5 m from the upper edge of the column proper, through which samples of the dispersion were taken off. In the distance 1·8 m of the upper edge an ultrasonic holdup sensor was placed. Within the column a system of perforated plates was situated and connected with the reciprocating drive. Two perforated plate types were investigated: the VPE plates with downcomers for continuous phase and simple sieve plates. Both plate types had perforations of 0·3 cm diameter. The specific free area of the VPE plate perforations was 10% and that of the three cylindrical downcomers was 18·3%. The specific free area of the sieve plates was 30%. The 4 cm long downcomers were directed upwards.

Two types of reciprocating drive were used: an eccentric with adjustable eccentricity connected with an electronically controlled variable speed motor and a linear electromagnetic reciprocating drive with remote amplitude and frequency control. Whereas the form of motion of the former drive was strictly harmonic, that of the latter was markedly deformed, as it could be seen on the oscillope screen.

1,2-Dichloroethane and water were used with the organic phase dispersed. Digital control of flow rates and interface level, as well as monitoring of flow rates and temperature of phases, amplitude and frequency of plate motion and holdup readings of the ultrasonic sensor were performed by a microcomputer controller. The liquids used were of technical grade. Both organic and water phase were recirculated. The density and viscosity of DCE at 25°C were 1 242·5 kg/m^3 and 7·9 . 10^{-4} kg/ms, respectively. The interfacial tension of the system measured by the sessile drop method was 0·0216 N/m, in comparison with the published experimental value[1,2] 0·0278 N/m for pure system. The lower interfacial tension of the system used was probably due to contamination with surfactants. The system exhibited low coalescence rates but its properties remained constant during the whole period of experiments lasting for almost a year.

Seven experimental configurations were investigated comprising the two types of plates, sets of plates with varying plate spacing, and the two types of reciprocating drive. These conditions are summarized in Table I. The results with sets IV to VI and X, XI have not been included into the parameter evaluation. The range of operating variables was: $2a \in \langle 0.2; 0.8 \rangle$ cm; $f \in \langle 1.0; 6.0 \rangle$ Hz; $Q_d \in \langle 0.76; 3.27 \rangle$ l/min; $Q_c \in \langle 0.19; 1.64 \rangle$ l/min ($U_d \in \langle 2.22; 9.59 \rangle$ mm/s; $U_c \in \langle 0.57; 4.83 \rangle$ mm/s).

Tentative experiments were performed with a dispersed phase distributor with 1 mm diameter perforations with a hole velocity 1·0—4·3 m/s. Under these conditions very fine droplets were produced the mean drop size of which did not change in the column with varying intensity of

TABLE I

Experimental configurations — column geometry and drive

Set	Exp. No.	h, m	ε_d	ε_c	d_h, m	Drive
I	29—98 257—262	0·098	0·10	0·183	0·003	linear
II	99—120	0·146	0·10	0·183	0·003	linear
III	121—151	0·067	0·10	0·183	0·003	linear
VII	263—325	0·098	0·10	0·183	0·003	eccentric
VIII	326—403	0·100	0·30	0·	0·003	eccentric
IX	404—461	0·053	0·30	0·	0·003	eccentric
XII	496—504	0·100	0·10	0·183	0·003	eccentric

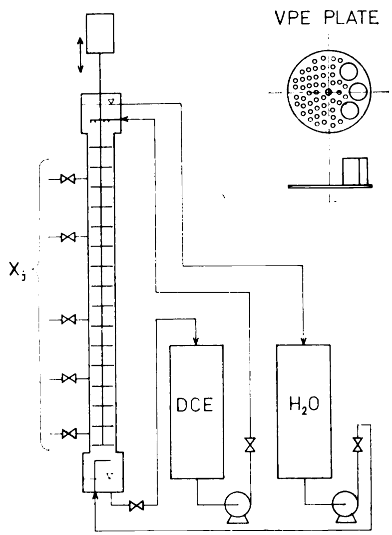

FIG. 1

Scheme of the experimental equipment

vibrations. This phenomenon can be explained by the low coalescence rates of the liquid system used. Therefore in the main body of experiments a distributor with 4 mm diameter perforations and with the hole velocity 0·1—0·43 m/s was used, which produced drop sizes of several millimeters. Under these conditions the drop size and the dispersed phase holdup were sensitive to the intensity of reciprocating motion.

In the individual experiments local holdup values were determined by taking cca 100 cm^3 samples of the dispersion at the individual sampling points. With the exception of regimes approaching closely the flooding point steady state was reached within 15 min. The samples were withdrawn starting from the lowest sampler upwards in intervals not shorter than 2 min. Reproducibility of these measurements at $X \geqq 0.1$ was ± 0.015. As the samplers were located in the midst of the stage height, the values obtained were ascribed to the holdup in the zone of hindered settling of the stage. At high phase velocities and low vibrational intensities a layer of densely packed dispersion formed at the plates. In each experiment a mean total holdup, X_t, was also determined by the switching off method. The mean error of X_t was ± 0.006.

In several experiments flooding of the column was observed. It started usually in some stage in the lower part of the column and was gradually spreading upwards to the dispersed phase distributor.

THEORETICAL

Countercurrent Flow

Vertical motion of drops in the zone of hindered settling in the j-th stage is described by the equation of "slip velocity"

$$u_{0,j}(1 - X_j)^{\alpha} = U_c/(1 - X_j) + U_d/X_j \,. \quad (1)$$

The characteristic velocity $u_{0,j}$ is a quantity approaching the terminal velocity $u_{t,j}$ of the mean drop size but not identical with it. According to Vohradský[3], who measured local mean vertical velocities of single droplets within a stage of the Karr reciprocating plate contactor, the droplets were increasingly retarded near the plate but even far from it their velocity was lower than the terminal velocity. Therefore

$$u_{0,j} = u_{t,j}/k_{ut} \,, \quad k_{ut} \geqq 1 \quad (2)$$

has been taken in the model. For $u_{t,j}$ the formula of Míšek and Marek[4] has been adopted

$$u_{t,j} = 0.249\,[(\Delta\varrho g)^2/\varrho_c\mu_c]^{1/3}\, d_j = p_3 d_j \,. \quad (3)$$

This formula is valid in the transitional region of drop velocities. For large oscillating drops Ishii and Zuber[5] proposed

$$u_m = [2(\sigma\, \Delta\varrho g)^{0.5}/\varrho_c]^{0.5} \,, \quad (4)$$

so that for both regions holds

$$u_{t,j} = \min \{p_3 d_j; u_m\} . \tag{5}$$

Drop Size

In systems with low coalescence rates the drops of mean diameter d_1 produced by the distributor undergo gradual breakage during their passage through individual plates and their mean size approaches a limiting value d_∞, which depends only on the amplitude and frequency of vibrations, the pulse shape, the plate geometry and spacing and on physical properties of the liquid system. The inevitable polydispersity of the system connected with the breakage process is not taken into account in the model. The degree of completion of this process in the j-th stage can be expressed by the dimensionless variable $(d_j/d_\infty - 1)$. In the model an exponential rate of change of the mean drop size with this variable is proposed

$$(d_{j+1} - d_\infty)/(d_j - d_\infty) = \exp\left[-k_p(d_j/d_\infty - 1)\right] , \tag{6}$$

in which the value of constant k_p depends on the plate type.

Equation (6) for $j = 1, 2 \ldots, N - 1$ determines the drop size profile in the column and by means of Eqs (2) to (5) the profile of characteristic velocities can be obtained. For calculating the drop size profile according to Eq. (6) the diameter of drops produced by the distributor, d_1, and the limiting value d_∞ must be known. For calculating d_1 use was made of the work of De Chazal and Ryan[6], Skelland and Johnson[7] and Horvath et al.[8].

The size of drops produced by the distributor depends on the liquid velocity in the openings of the distributor (nozzle velocity, v_N) and on the diameter of these openings d_N. Whole range of v_N is divided into three regions by jetting velocity v_J and critical velocity v_C. For $v_N < v_J$, single drops are formed. For $v_J \leqq v_N < v_C$, a jet is formed at each opening, the length of which grows and the size of drops formed by jet disintegration diminishes with v_N. For $v_N \geqq v_C$, the jet has its maximum possible length and the size of drops formed by jet splitting is uniform.

Drop size in the first region depends on the drop terminal velocity. It can be calculated iteratively from the correlation[6]

$$d_1^3 = (6 d_N \sigma/\Delta\varrho g)\,(\psi + 0{\cdot}664 g\, \Delta\varrho d_N d_1 v_N/\sigma u_t - 0{\cdot}4285 d_N \varrho_d v_N^2/\sigma)$$
$$\text{for} \quad v_N < v_J\,, \quad \psi = 0{\cdot}625\,, \tag{7}$$

$$v_J = 1{\cdot}07(2\sigma/\varrho_d d_N)^{0.5} - 0{\cdot}75(\Delta\varrho g d_N/2\varrho_d)^{0.5} \tag{7a}$$

together with Eq. (5).

Critical velocity v_C and the corresponding jet diameter d_C are[7]

$$v_C = 2{\cdot}69(d_C/d_N)^2\,[\sigma/d_C(0{\cdot}514\varrho_d + 0{\cdot}472\varrho_c)]^{0.5}\,, \tag{8}$$

$$d_C = \begin{cases} d_N/(0{\cdot}485K^2 + 1{\cdot}0) & \text{for} \quad K < 0{\cdot}785 \\ d_N/(1{\cdot}51K + 0{\cdot}12) & \text{for} \quad K \geqq 0{\cdot}785 \end{cases} \tag{8a}$$

$$K = d_N/(\sigma/\Delta\varrho g)^{0.5} \tag{8b}$$

and the size of drops formed above the critical velocity is[8]

$$d_1 = 2{\cdot}07 d_C \quad \text{for} \quad v_N \geqq v_C\,. \tag{8c}$$

Drop size for the intermediate nozzle velocities is described by an empirical equation[8]

$$d_1/d_C = 2{\cdot}06/(v_N/v_C) + 1{\cdot}47\ln(v_N/v_C) \quad \text{for} \quad v_J \leqq v_N < v_C\,. \tag{9}$$

The limiting drop diameter d_∞ can be assessed using the Sauter mean diameter correlation[9]

$$d_{32} = 1/[1/d_{32}'^2 + 1/(0{\cdot}81\sigma/\Delta\varrho g) + 1/d_h^2]^{0.5}\,, \tag{10}$$

$$d_{32}' = 0{\cdot}116(\sigma/\varrho_c)^{0.6}\,[\varepsilon_p^2 z/(1 - \varepsilon_p^2)]^{0.4}\,I^{-1.2}\,, \tag{10a}$$

$$I = k_3 a^{0.9} f^{1.1}\,, \tag{10b}$$

$$z = \min\{0{\cdot}17\varepsilon_q^{-0.33} I^{0.5};\, h\}\,, \tag{10c}$$

$$\varepsilon_p = \varepsilon_d/(1 - \varepsilon_c)\,; \quad \varepsilon_q = \varepsilon_d + \varepsilon_c\,. \tag{10d}$$

The coefficient k_3 in Eq. (*10b*) depends on the shape of the periodic motion of plates and accordingly on the type of the drive. In case of harmonic motion $k_3 = 1$. As shown by Míšek[10], it would be appropriate to use d_{43}, which is greater than d_{32}, for calculating the characteristic velocity. Accordingly, for obtaining correct value of d_∞ the Sauter mean diameter should be multiplied by a factor greater than 1. On the other hand, as shown by Koshy[11], if surface active agents are present in the system, drop breakage is facilitated by the interfacial tension gradients and a factor smaller than 1 should be applied. In view of this uncertainty d_∞ was identified with d_{32} in evaluating the experiments of this work. In calculating the characteristic velocity the possible differences between d_{32} and d_∞ were thus transferred to the value of k_{ut}.

Holdup and Flooding

For $\alpha > 0$ and u_0 great enough Eq. (*1*) possesses two real solutions on the interval

$X \in \langle 0; 1 \rangle$. The lower value corresponds to the unsupported steady state countercurrent flow and the higher one to the densely packed dispersed phase.

When the characteristic velocity $u_{0,j}$ decreases, e.g. by increasing vibrational intensity at constant U_c, U_d, the two solutions of Eq. (*1*) approach each other and finally merge in the critical (flooding) point. Similarly a critical point may be reached by increasing U_d or U_c, other variables being constant. Accordingly the so called "flooding by excessive vibrations" can be defined by

$$(\partial u_0/\partial X)_F = (\partial U_c/\partial X)_F = (\partial U_d/\partial X)_F = 0 . \quad (11)$$

Solving Eqs (*1*) and (*11*) the relations for critical holdup and critical characteristic velocity can be derived

$$X_F = \{2 + \alpha - [\alpha^2 + 4(1 + \alpha) r]^{0.5}\}/2(1 + \alpha)(1 - r) , \quad (12)$$

$$u_{0F} = U_{dF}(1 - X_F + X_F r)/X_F(1 - X_F)^{\alpha+1} ; \quad r = U_{cF}/U_{dF} . \quad (13)$$

A densely packed layer appears at each plate whenever the plate exerts an appreciable resistance to the motion of the dispersed phase, e.g. at low intensity of vibrations, high dispersed phase flow rate, small diameter of plate perforations and their low specific free area. Such conditions are usually described as the mixer-settler regime. The specific holdup of the dispersed phase in this layer and the thickness of the layer may vary with the mean drop size, the density difference of the phases, their flow-rates and the fluidizing action of the countercurrent flow of the continuous phase and the plate vibration. In the present model, however, an equivalent thickness of a fully coalesced layer is introduced, which is numerically equal to the product of the holdup of the dispersed phase in the layer related to the stage volume, X_v, and the stage height, h.

For X_v a semiempirical correlation has been proposed

$$X_v = (k_v/h)[U_d/(2af - U_c/2)]^2 , \quad (14)$$

which fits well the data available; k_v is the parameter of the layer.

The total holdup in stage j, $X_{t,j}$, is related to the holdup in the densely packed layer X_v and the holdup in the zone of unsupported countercurrent flow, X_j, by

$$X_{t,j} = X_j(1 - X_v) + X_v \quad (15)$$

and the total mean holdup in the column with N stages is

$$X_t = \sum_{j=1}^{N} (X_j/N)(1 - X_v) + X_v . \quad (16)$$

According to Eq. (*14*) X_v is supposed to be constant for all stages and can be determined from measured holdup profiles and the total mean holdup as

$$X_v = (X_t - S)/(1 - S) \; ; \quad S = \sum_{j=1}^{N} X_j/N \, . \tag{17}$$

In the sieve-plate columns, flooding can take place at low vibrational intensity. With decreasing intensity the relative equivalent thickness of the densely packed layer X_v increases and so does its actual thickness. In the case of sieve plates it may happen that the layer fills the whole stage and the so called „flooding by insufficient vibrations" occurs. The flow structure near flooding by insufficient vibrations is unstable and small disturbances in flow rates or intensity of vibrations may advance flooding. Therefore a term proportional to U_d was introduced into Eq. (*14*) for sieve plates near flooding to account for this instability,

$$X_v = (k_v/h) \left[U_{dF}/(2af - U_{cF}/2)\right]^2 + k_F U_{dF} \, . \tag{18}$$

Flooding point was then calculated iteratively searching for $X_{t,j} = X_F$, with $X_{t,j}$ from Eqs (*15*), (*1*), (*18*) and X_F from Eq. (*12*).

In the case of VPE plates flooding by insufficient vibrations has not been observed. The thickness of the densely packed layer is limited by the downcomers which allow it to overflow to the next stage. The maximum X_v was identified as

$$X_{v\max} = (k_v/h) (U_d/k_m)^2 \, , \quad k_m = 0.007 \text{ m/s} \tag{19}$$

and the critical point determined from Eqs (*12*) and (*13*).

RESULTS AND DISCUSSION

Evaluation of Model Parameters

Program VYPARA was used for evaluating the model parameters k_{ut}, k_p and α, which minimize the mean square deviation of experimental holdup profiles and those calculated by Eq. (*1*). Only experiments in which no incipient flooding was observed were evaluated. Parameters k_{ut}, k_p determine the profile of local characteristic velocity $u_{0,j}$ and are supposed to be constant for a given type of plates.

Systematically lower simulated holdups were obtained at high vibrational intensities; for the plate spacing 0·1 m at $I > 0.026$ m/s, for the plate spacing 0·055 m at $I > 0.022$. This is in concord with Vohradský's findings that k_{ut} increases at higher intensities of vibrations[3]. These experiments were therefore not included in the final evaluation of parameters, which gave optimum values $k_p = 0.11$ for the VPE plates, $k_p = 0.50$ for the sieve plates and $k_{ut} = 1.40$ for both plates.

Parameter α was first supposed to be constant and was evaluated as $\alpha = 1{\cdot}6$ for all experiments. However, several authors have found changes of α with the intensity of vibration/pulsation, using Eq. (*1*) for correlating total dispersed phase holdup in various types of extractors. Thus Heyberger, Sovová and Procházka[12] have demonstrated that Eq. (*1*) proposed originally by Richardson and Zaki[13] for holdup in fluidized beds can be well applied to reciprocating plate columns VPE. The values of α for five columns of varying diameter and length are plotted in Fig. 2. With the exception of the column No. 3 the values are within $1{\cdot}25 \leqq \alpha \leqq 2{\cdot}20$ and show a decreasing trend with increasing vibrational intensity. Slater used Eq. (*1*) for correlating total holdups in extractors of various types. According to Hussain, Liang and Slater[14] the value of α was generally decreasing with increasing mixing intensity. For pulsed columns they proposed

$$\alpha = 0{\cdot}16 Re_k^{0.66}\ ; \quad \text{for} \quad 2 < Re_k < 125\ ; \quad Re_k = d\varrho_c u_0/\mu_c\ . \qquad (20)$$

For cases in which the drop diameter was not measured, they used the mean drop size correlation[15]

$$d = 0{\cdot}439 d_h (\sigma \varepsilon_p^{0.5}/d_h \varrho_c)^{0.6} (2\pi a f + U_c)^{-1.2}\ . \qquad (21)$$

Dependence of α evaluated for the conditions of our experiments according to Eqs (*20*), (*21*) is also depicted in Fig. 2. Also Mersmann[16] correlated α with hydrodynamic characteristics of drops but instead of the Reynolds number he used the Archimedes criterion.

In contrast to the works quoted, in the present work Eq. (*1*) has been applied to the local holdups within the stages and thus the values of α obtained are free of the effect of the densely packed layers as well as of the deformation caused by averaging

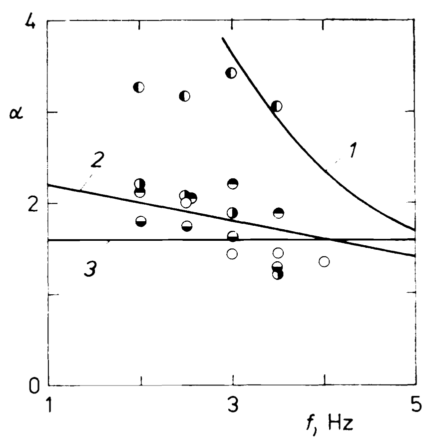

FIG. 2

Values of exponent in Eq. (*1*); $a = 2$ mm. Data Heyberger et al.[12]: ○ column No. 1, ◑ No. 2, ◐ No. 3, ◓ No. 4, ◒ No. 5. Curves of correlations: *1* Hussain et al.[14], *2* this work, sets I–VII, *3* this work, sets VIII–XII the holdup profiles. To prove the suggestion by Slater and coworkers, the second evaluation of α was performed in dependence of vibrational intensity for experiments with individual sets of plates.

This investigation discovered a moderate decline of α with the amplitude-frequency product for sets I do VII but no effect for sets VIII to XII. For the former sets the relation

$$\alpha = 2{\cdot}4 - 100af\,, \quad 0{\cdot}004 \leqq 2af \leqq 0{\cdot}024 \text{ m/s} \tag{22}$$

was introduced. On the other hand, any dependence of α on the drop diameter which varied strongly along the column was entirely incompatible with the measured holdup profiles.

In this work the parameter α was evaluated for a single binary liquid system which, probably due to some contamination, exhibited low coalescence rates. It is believed that widely differing values of this parameter found by other authors are due mainly to the coalescence properties of the particular systems used. The present model is based on the assumption that the effects of breakage and coalescence can be separated into different terms of Eq. (*1*), namely the former into $u_{0,j}$ or d_j and the latter into $(1 - X_j)^\alpha$. The weak dependence (*22*) may be viewed as a secondary effect. It is well known that the coalescence rate depends on the composition and physical properties of the liquid system, on the mass transfer rate and direction, on the contamination by surfactants and also on the degree of wetting of the extractor interiors. Let us suppose that the drop size and characteristic velocity in absence of coalescence would be d_j, $u_{0,j}$ and, due to coalescence, they increase to d'_j, $u'_{0,j}$. This increase may be expressed by a power function

$$u'_{0,j} = u_{0,j}(1 - X_j)^{-\beta}\,, \quad \beta > 0\,, \tag{23}$$

where β is a parameter characterizing the effect of coalescence. Equation (*1*) can be rewritten in the form

$$u_{0,j}(1 - X_j)^{\alpha_0 - \beta} = U_c/(1 - X_j) + U_d/X_j\,, \tag{24}$$

where α_0 is the value of the exponent for noncoalescing systems. This is an analogy to the equation with coalescence factor Z introduced by Míšek[17]

$$u_{0,j}(1 - X_j)\exp\left[-(4{\cdot}1 - Z)\,X_j\right] = U_c/(1 - X_j) + U_d/X_j\,. \tag{25}$$

The coefficient of effective vibrational intensity in Eq. (*10b*) for linear drive $k_3 = 1{\cdot}3$ allowed to approximate the data but a better fit was obtained with

$$I = 0{\cdot}52(a^{0.9}f^{1.1})^{0.8}\,. \tag{26}$$

This is consistent with the finding of Thornton[18] that the effective intensity for a stepwise pulse can be less dependent or even independent of its amplitude and frequency.

The parameter values obtained by VYPARA were taken as a basis for simulating all experiments, including those at incipient flooding, using the simulation programs MODEL5 for the VPE and MODEL6 for the sieve plates. In these programs also the relations for flooding and the total holdup X_t are incorporated. By comparing these results with experimental data the parameter of the layer $k_v = 0{\cdot}007$ m and of the instability near flooding $k_F = 30$ s/m were obtained. Standard deviations of the calculated values from measured ones were 0·012 for the total holdup and 0·023 for the local holdups.

Holdup Behaviour

Several examples of the holdup behaviour are given in the next figures. Full lines mark the results of simulations.

In Fig. 3 the change in holdup profile caused by an increase of U_d leading to flooding of the column is demonstrated. Both profiles have been simulated by Eq. (*1*). Below the critical point the smaller of the two roots of Eq. (*1*), at flooding the greater one is valid. Flooding starts in the stage in which u_0 drops under its critical value. In all preceeding stages the conditions are below the critical ones and Eq. (*1*) has there two roots.

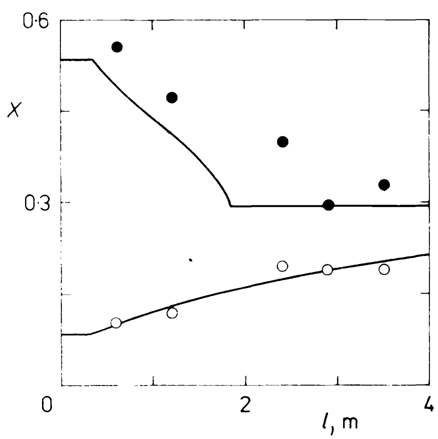

FIG. 3

Holdup profiles below and above flooding point; $U_c = 2{\cdot}7$ mm/s, $a = 1{\cdot}2$ mm, $f = 3{\cdot}75$ Hz. ○ Exp. 42, $U_d = 5{\cdot}76$ mm/s; ● exp. 44, $U_d = 7{\cdot}20$ mm/s

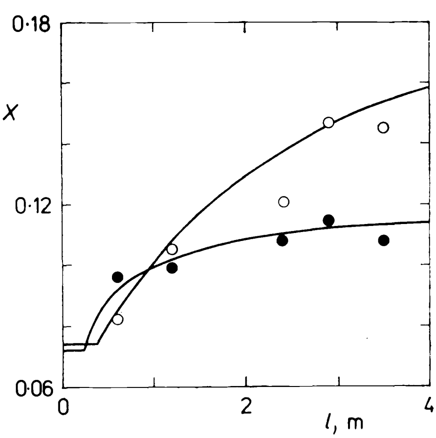

FIG. 4

Holdup profiles for different types of plates; $U_d = 5{\cdot}29$ mm/s, $U_c = 2{\cdot}7$ mm/s, $a = 2$ mm, $f = 3$ Hz. ○ Exp. 283, VPE plates; ● exp. 328, sieve plates

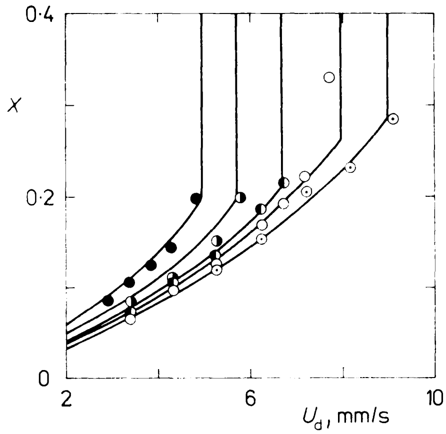

FIG. 5

Total holdup in the column, set VII; U_c = = 2·7 mm/s, a = 2 mm. ⊙ f = 1 Hz, ○ f = 2 Hz, ◐ f = 3 Hz, ◑ f = 4 Hz, ● f = = 5 Hz

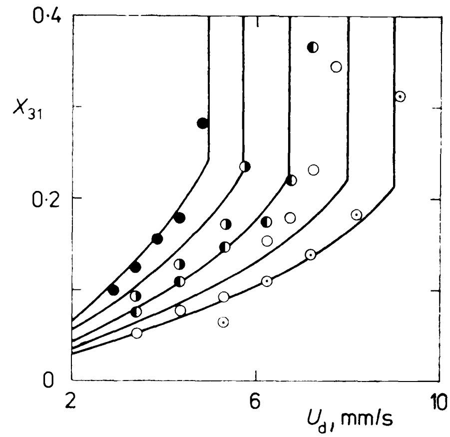

FIG. 6

Local holdup in the 31st stage; conditions as in Fig. 5

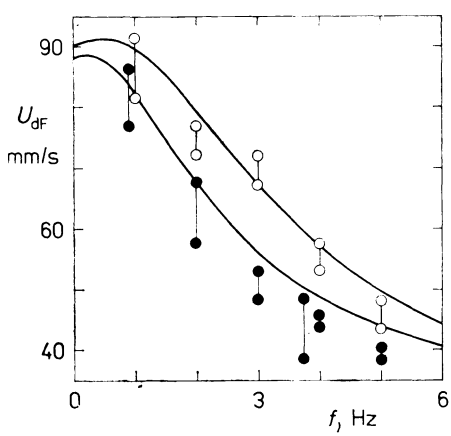

FIG. 7

Flooding in column with VPE plates; h = = 0·10 m. U_c = 2·7 mm/s, a = 2 mm. ○ Set VII, motor with eccentric; ● set I, linear drive

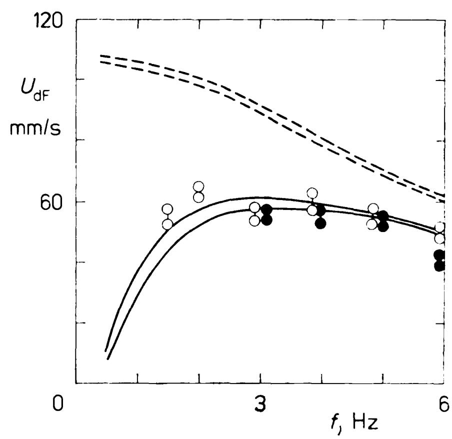

FIG. 8

Flooding in column with sieve plates; U_c = 2·7 mm/s, a = 2 mm. ○ Set VIII, h = 0·10 m; ● set IX, h = 0·053 m

Difference between the rising holdup profiles on VPE plates with $k_p = 0{\cdot}11$ and the relatively flat profiles on sieve plates with $k_p = 0{\cdot}50$ is demonstrated in Fig. 4. The effect of dispersed phase flow rate and frequency on X_t for a set of VPE plates driven by the eccentric is depicted in Fig. 5. At low mixing intensity the total holdup increase with frequency is only moderate because the increasing holdup within the stage is partially compensated by the decreasing thickness of the densely packed layer. More pronounced is the increase of local holdup in the settling zone which is shown for identical conditions in Fig. 6.

Prediction of critical conditions by the mathematical model is demonstrated in Figs 7 and 8. Here the pairs of experimental points represent the phase velocities just below and above critical point. For the VPE plates (Fig. 7) the critical velocity decreases with increasing intensity of vibrations. For the sieve plates (Fig. 8) an ascending part of the curve at low intensities of vibration appears. Prediction of flooding by the model is comparatively reliable for both types of plates. For the same characteristic velocities, flooding in the column with sieve plates occurs earlier than in the column with VPE plates, because on the sieve plates the densely packed layer of dispersion fills the whole stage before the conditions of flooding in the settling zone have been reached. The dashed lines in Fig. 8 indicate the flooding limit calculated for the hypothetical case of no densely packed layer.

CONCLUSIONS

1. The measurements of local holdup in the settling zones of the stages have detected pronounced holdup profiles which could be described by a model of gradual breakage of drops.

2. The breakage intensity was shown to depend on the form of reciprocating motion of plates. With a linear electromagnetic drive with deformed motion, in comparison with a drive with harmonic motion, the breakage was more intensive at a given amplitude and frequency but less dependent on vibrational intensity.

3. The plates of the VPE type and the sieve plates were compared. The higher capacity of the VPE plates in the region of flooding by insufficient vibrations known earlier was confirmed. Newly a higher stability of the VPE plates in the regimes of intensive vibrations has been discovered which allows to operate these plates safely at higher throughputs.

4. The changes in wetting of plates by dispersed phase were identified as the main factor influencing the reproducibility of experiments. After eliminating this effect good reproducibility was attained.

5. The model proposed contains five parameters, three of which are related with the hydrodynamics of countercurrent flow within the stage, one determines the thickness of the densely packed layer at the plate and one is used with sieve plates providing

for the hydrodynamic instability near flooding and with VPE plates to limit the thickness of the layer. The program VYPARA performs automatic evaluation of the first three parameters from local holdup measurements. It can be expected that in systems with high coalescence rate flat holdup profiles will occur and only two of these parameters, α and k_{ut}, might be sufficient. Evaluation of the last two parameters, k_v and k_F or k_m, from total holdup measurements is straightforward.

6. The dependence of α on vibrational intensity has been found unconspicuous.

SYMBOLS

a	amplitude of reciprocation (half stroke), m
d	drop diameter, m
d_{32}	Sauter diameter, m
d'_{32}	Sauter diameter resulting from drop splitting by plate reciprocation, m
d_h	diameter of plate openings, m
f	frequency of reciprocation, Hz
g	acceleration of gravity, m/s^2
h	plate distance, m
I	effective intensity of reciprocation, m/s
k_m	coefficient in Eq. (*19*), m/s
k_p	coefficient in Eq. (*6*)
k_{ut}	$= u_t/u_0$ parameter
k_v	coefficient of densely packed layer, m
k_3	parameter in Eq. (*10b*), (m s)$^{0.1}$
K	criterion defined by Eq. (*8b*)
l	distance from the top of column, m
N	number of stages in column
p_3	coefficient in Eq. (*3*), Hz
Q	flow rate, m^3/s
r	$= U_c/U_d$ ratio of continuous and dispersed phase flows
Re_k	Reynolds number, defined by Eq. (*20*)
s	standard deviation of holdup
u_0	characteristic velocity, m/s
u_m	terminal velocity of oscillating drops, m/s
u_t	terminal velocity, m/s
v	liquid velocity in the openings of distributor, m/s
U	superficial velocity, m/s
X	dispersed phase holdup in the settling zone
X_v	dispersed phase holdup in densely packed layer
X_t	total dispersed phase holdup
z	height of splitting zone, m
α	exponent in Eq. (*1*)
β	coefficient of coalescence in Eq. (*23*)
$\Delta\varrho$	density difference, kg/m^3
ε_d	relative free area of openings of diameter d_h
ε_c	relative free area of openings with overflows
ε_p, ε_q	effective relative free areas according to Eq. (*10d*)

μ viscosity, kg/(ms)
ψ correction factor for drop volume
ϱ density, kg/m^3
σ interfacial tension, N/m

Subscripts

c continuous phase
C critical
d dispersed phase
F flooding
j number of stage or plate in the direction of dispersed phase flow
J jetting
N nozzle
∞ asymptotic value after passage through an infinite number of plates

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