POLYDISPERSE MODEL OF THE VPE EXTRACTOR HYDRODYNAMICS

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A computer simulation model of the dispersed phase holdup in the vibrating-plate extractor was developed. Drop transport, breakage and coalescence equations were solved simultaneously, the stage being divided in the internal part and in the dense-packed layer of dispersion at the plate. The verified simulator can be used to predict and to analyse both steady state holdup and its dynamics and it can help to design a VPE extractor or a pulsed sieve-plate extractor. Holdup measured in a VPE column with toluene dispersed in water without mass transfer was simulated by the model with a standard deviation 6% rel. in the whole range from the mixer-settler region to the emulsion region.

Vibrating-plate extractor VPE[1,2] is one of the efficient industrial liquid–liquid extractors. It is equipped with vibrating perforated plates which bring dispersion to turbulent motion and split the drops (Fig. 1). The plates are provided with small holes for the dispersed phase and with large openings for the continuous phase. In comparison with a common sieve plate this arrangement ensures higher throughputs.

Similarly to the pulsed sieve-plate columns, several flow regimes have been observed in VPE. In the *mixer-settler regime* with low vibration intensity large drops quickly pass the stage and accumulate in a layer at the plate. They are pumped by plate vibrations to the next stage. Total dispersed holdup falls with increasing vibration intensity. In the *dispersion regime* with medium vibration intensity the drops are smaller, their residence time inside the stage increases, while the layer at the plate narrows down, because its pumping is quicker. There are more drops inside the stage than in the layer and the total holdup grows with vibration intensity. In the *emulsion regime* with high vibration intensity the drops are small, the dispersed phase holdup is high and uniform in the whole stage. Holdup increases steeply with vibration intensity up to the flooding.

The dependence of holdup on the vibration or pulsation intensity was described by separate correlations for individual regimes[3] or by an empiric parabolic function[4]. In the hydrodynamic models of pulsed sieve-plate columns[5,6] and of the VPE[7] the plates were not supposed to slow down the flow of dispersion and therefore these models were limited to the dispersion and emulsion regimes. Model of the mixer-settler regime[8] described the holdup in the dense-packed layer at the plate only.

Combining the dependencies of the holdup inside the stage and of the holdup in the layer, all regimes can be covered up by a single hydrodynamic model, as is shown in this paper. Model parameters are adjusted according to the earlier performed experiments[9].

Model Structure

The polydisperse model was derived similarly to the model of Karr column[10]. Though a constant liquid density was supposed, the model can be extended to the case of density variable along the column. Periodic quantities (liquid velocities, holdup, height of the layer) are described by their average value. The stage is divided in the inner part and in the layer of dense-packed dispersion at the plate with height depending on the plate vibration intensity. For the sake of simplicity, a layer of zero voidage is considered. With the stage height h, the layer height H_i and the holdup inside the stage X_i, the total holdup in the i-th stage is

$$X_{ti} = X_i + (1 - X_i) H_i/h \,. \qquad (1)$$

Drop flow between the column sections is shown in Fig. 2. The velocity u_s from the inner part of the stage to the layer is given by a countercurrent two-phase flow equation. The velocity of drop pumping from the layer to the next stage u_v increases with the plate vibration intensity and with the layer height. The velocity of drop

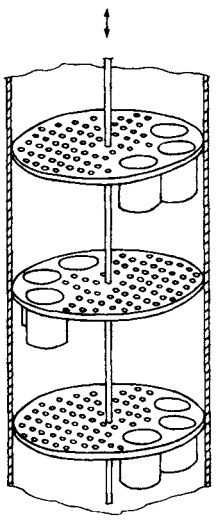

FIG. 1
Arrangement of the VPE plates

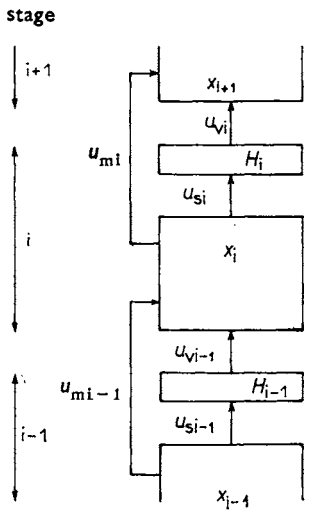

FIG. 2
Scheme of the dispersed phase flow

axial mixing u_m is calculated of the total displacement of liquid pumped across the plate in both directions.

Dispersion is composed of drops with a diameter d^j,

$$d^j = d^1 j\,, \quad j = 1, 2, \ldots, M\,. \tag{2}$$

Holdups and layer heights of the individual size fractions X_i^j, H_i^j are calculated in each stage. The overall holdup inside the stage i is

$$X_i = \sum_{j=1}^{M} X_i^j\,, \tag{3}$$

the height of the layer is

$$H_i = \sum_{j=1}^{M} H_i^j\,. \tag{4}$$

Drop breakage and coalescence are simulated by a shift of an appropriate volume of drops from higher size fractions to lower ones and *vice versa*.

The rates of changes of the fractional holdups X_i^j and of the fractional layed heights H_i^j resulting from drop transport, breakage and coalescence are describer by a set of ordinary non-linear differential first-order equations. By their numerical integration the transient behaviour of holdup profiles $X_i^j(t)$, $H_i^j(t)$ are obtained.

Model Equations

Dispersed phase superficial velocity from the inner part of the stage to the layer is

$$u_{si}^j = \left[u_t^j(1 - X_i) - k_u U_c/(1 - X_i)\right] X_i^j\,, \quad j = 1, 2, \ldots, M\,. \tag{5}$$

Parameter $k_u \geqq 1$ depending on the column geometry was used by King and Beckman[11] to describe the holdup in RDC extractor.

Superficial velocity of drops across the plate is calculated as

$$u_{vi} = \sum_{j=1}^{M} u_{vi}^j = k_v(2af - U_c/2)\, H_i^b\,. \tag{6}$$

Driving force of the layer pumping is proportional to the plate vibration intensity $2af$ decreased by the effect of continuous phase flow. Superficial velocities of the individual size fractions are consequently

$$u_{vi}^j = k_v(2af - U_c/2)\, H_i^j/H_i^{1-b}\,, \quad j = 1, 2, \ldots, M\,. \tag{7}$$

If the layer height reaches the edge of downcomers, the velocities u_{vi}^{j} should involve also the drops rising freely through the large openings in the plate.

The difference between the mean plate velocity $2af$ and the velocity of the layer pumping u_{vi} is equal to the velocity of dispersion pumping from the inside of the stage i to the stage $i + 1$. Superficial velocity of the j-th fraction flow is $(2af - u_{vi}) X_i^j$. With a symmetrical pumping in the opposite direction, the overall axial mixing is

$$u_{mi}^{j} = (2af - u_{vi})(X_i^j - X_{i+1}^j), \quad j = 1, 2, \ldots, M . \tag{8}$$

The transport parameters in Eqs (5)–(7), $k_u = 2{\cdot}8$, $k_v = 9{\cdot}9\ \mathrm{m}^{-2/3}$, $b = 0{\cdot}67$ were evaluated minimizing the sum of squares of deviations between the calculated and measured holdups. The first estimate of the parameter values was obtained from simplified equations. In the steady state and with a flat holdup profile it holds $u_m = 0$, $u_s = u_v = U_d$. Parameters k_v, b were estimated inserting experimental values U_d, $2af$, U_c, H into Eq. (6), the layer height H being calculated of experimental holdups X_t, X according to Eq. (1). Parameter k_u was estimated from the experiments with an equal amplitude and frequency of vibration, equal holdup X and different phase velocity ratio. Reducing Eq. (5) to one size fraction and putting $u_s = U_d$ one gets

$$k_u = [u_t(1 - X)^2 - U_d(1 - X)/X]/U_c . \tag{9}$$

As u_t = const. at constant a, f, values U_c, U_d, X of two experiments suffice to calculate k_u.

Drop breakage is defined by breakage frequency $g(d)$ of a drop having diameter d, by number of daughter drops d' per one breakage $\nu = 2$ and by daughter drop probability density $\beta(d, d')$. The breakage frequency is given by an empirical formula

$$g(d) = 1{\cdot}2 \exp\left[1{\cdot}5f(a/0{\cdot}002)^{0{\cdot}75}\right](d - 0{\cdot}0014);\ g \geqq 0 . \tag{10}$$

Critical drop size $d = 0{\cdot}0014$ m, below which the breakage ceases, is probably related to the size of plate holes. A volume uniform daughter drop distribution

$$\beta(d, d') = 3d'^2/d^3 \tag{11}$$

is assumed. To calculate the shift of drops between size fractions, Eqs (10), (11) are discretised.

Slow coalescence of drops affected the holdup negligibly. Evaluation of the coalescence dependence on drop size, layer height and vibration intensity was not possible. Therefore a simple description is used with a constant volume ratio of drops in the layer $\omega = 0{\cdot}005$ shifted per second from each size fraction $j = 1, 2, \ldots, M - 1$ to the next higher fraction.

Dispersion is represented by six size fractions from 0·5 to 3·0 mm with the largest drops entering the column.

EXPERIMENTAL

Experiments were performed by Heyberger and Ivanišević[9] in a 40 stage vibrating plate extractor with toluene dispersed in water. Commercial toluene and tap water with physical properties $\varrho_c = 999\ \mathrm{kg/m^3}$, $\varrho_d = 867\ \mathrm{kg/m^3}$, $\mu_c = 0{\cdot}00103\ \mathrm{kg/ms}$, $\mu_d = 0{\cdot}00059\ \mathrm{kg/ms}$, $\sigma = 0{\cdot}0343\ \mathrm{N/m}$ were used throughout.

Column dimensions were: internal diameter 0·085 m, efficient height 4 m, plate distance 0·1 m. The stainless steel plates had 0·003 m diameter holes resulting in an open area fraction of 0·10. Openings with 0·04 m high downcomers gave an open area fraction for continuous phase of 0·19. The superficial velocities were adjusted within the range $U_c = 1{\cdot}86 \cdot 10^{-3} - 5{\cdot}11 \cdot 10^{-3}$ m/s, $U_d = 1{\cdot}94 \cdot 10^{-3} - 4{\cdot}76 \cdot 10^{-3}$ m/s. Forty experiments were divided in eight sets with constant a, f, L inside each set (Table I).

Steady-state local holdups inside the stage were evaluated from the samples of dispersion taken of the middle of the 5th, 23rd and 35th stage, counted from the dispersed phase inlet. Total holdup in the column was determined by the method of sudden shutting down of inlets and outlets with an accuracy of $\pm 5\%$rel.

RESULTS

All measured and simulated profiles of holdup inside the stage are of similar shape. An example of the set No 3 holdups is given in Fig. 3. Holdup grows in the direction of the dispersed phase flow, because drop breakage prevails over drop coalescence. The holdup at the dispersed phase outlet is decreased by axial mixing. Standard deviation of the simulated local holdups from the measured ones is 13% rel.

Fig. 4 shows the total holdup for five sets of experiments, remaining three sets being dropped for the sake of simplicity. Standard deviation of simulated holdups

TABLE I
Operating variables

Set No	a, mm	f, Hz	L
1	2	2	1·16
2	2	2·5	1·16
3	2	3	1·16
4	2	4	1·16
5	2	3	0·58
6	2	3	2·32
7	3	2	1·16
8	4	2	1·16

from measured ones ranges from 3% rel. (sets No 6, 7) to 22% (set No 1), with an overall standard deviation 11% rel. Distribution of these deviations is not random. Maximum values are in the first experiment of the first set (+47% rel.) and in the

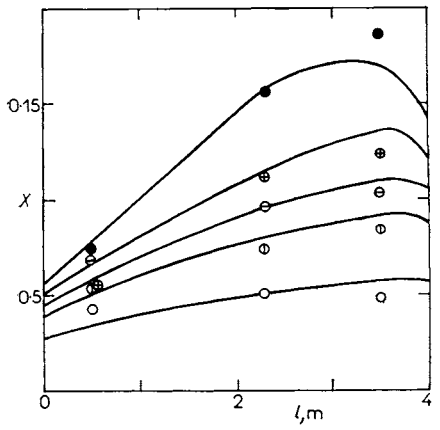

FIG. 3

Profiles of holdup inside the stage $a = 0{\cdot}002$ m, $f = 3$ Hz, $L = 1{\cdot}16$. Experiments: ○ $U_c = 0{\cdot}00186$ m/s, ⊙ $U_c = 0{\cdot}00255$ m/s, ⊖ $U_c = 0{\cdot}00281$ m/s, ⊕ $U_c = 0{\cdot}00309$ m/s, ● $U_c = 0{\cdot}00340$ m/s. Simulation ———

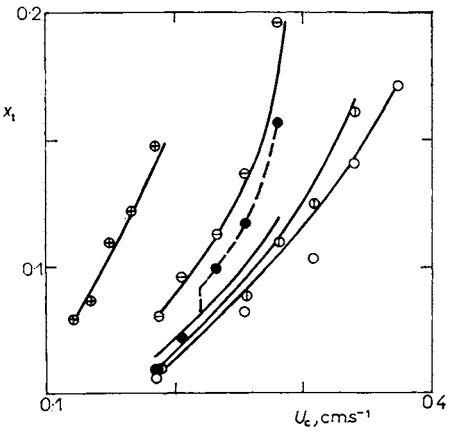

FIG. 4

Total holdup

Experiments: ○ set 2, ⊙ set 3, ⊖ set 4, ⊕ set 6, ● set 8. ——— simulation with $k_v = 9{\cdot}9\ \mathrm{m}^{-2/3}$, – – – simulation with variable k_v

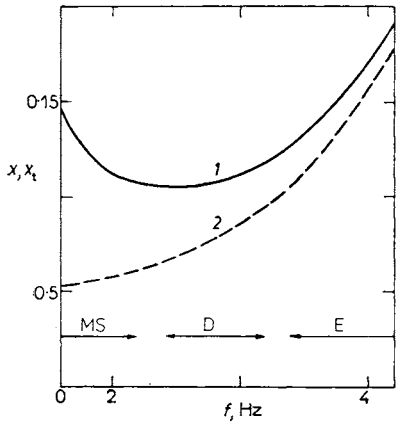

FIG. 5

Simulation of the effect of vibration intensity on holdup

$a = 0{\cdot}002$ m, $U_c = 0{\cdot}00281$ m/s, $L = 1{\cdot}16$, $k_v = 9{\cdot}9\ \mathrm{m}^{-2/3}$. *1* total holdup, *2* holdup inside the stage

last experiment of the last set (−24% rel.). Minor negative deviations are also in preceding two experiments of the set No 8. Standard deviation of the remaining 36 experiments is 6% rel.

Experiments No 1, 38–40 were simulated again, searching for the values of parameter k_v resulting in the measured total holdups. These values are $k_v = 19\ m^{-2/3}$ in exp. 1, $k_v = 6{\cdot}5\ m^{-2/3}$ in exp. 38, $k_v = 6{\cdot}3\ m^{-2/3}$ in exp. 39 and $k_v = 4{\cdot}8\ m^{-2/3}$ in exp. 40. Changes of k_v did not affect the accuracy of local holdup simulation. They correspond to a gradual decrease of the efficiency of drop pumping across the plate, which could be caused by accumulation of some impurities in the system.

Model ability of describing various extractor regimes is demonstrated in Fig. 5, showing both the holdup inside the stage and the total holdup. With increasing vibration intensity a transition from the mixer-settler regime with holdup concentrated mostly in the dense-packed layer to the emulsion regime with a nearly homogeneous stage is observed.

CONCLUSIONS

Hydrodynamic model of the vibrating plate extractor, which can simulate the pulsed sieve-plate column as well, describes

1) total holdup with a standard deviation of 6% rel.,
2) nonhomogeneity of holdup along the stage, distinguishing the holdup inside the stage and in the layer at the plate,
3) holdup profile along the column resulting from drop breakage, coalescence and axial mixing.

Model parameters are: coefficient k_u in the countercurrent flow equation, coefficient k_v and exponent b in the flow across the plate equation, and parameters of the drop breakage and coalescence equations. Parameters depend on the column geometry and on the liquid properties ϱ_c, ϱ_d, μ_c, μ_d, σ. Drop coalescence frequency is known to be affected also by mass transfer direction and by tracer amounts of impurities dissolved in liquids. According to the simulation results, the height of the dense-packed layer at the plate could be sensitive to the same influences.

LIST OF SYMBOLS

a	amplitude of plate vibrations
b	exponent, Eq. (6)
d	drop diameter
f	frequency of plate vibrations
g	drop breakage frequency
h	plate spacing
H	dense-packed layer height

k_u model parameter, Eq. (5)
k_v model parameter, Eq. (6)
L ratio U_d/U_c
M number of size fractions
u_m superficial velocity of axial mixing
u_s dispersed phase superficial velocity inside the stage
u_t drop terminal velocity
u_v dispersed phase superficial velocity across the plate
U phase superficial velocity at the column inlet
X dispersed phase holdup inside the stage
X_t total holdup of dispersed phase
$\beta(d, d')$ probable density of daughter drops
μ viscosity
ϱ density
σ interfacial tension

Subscripts

c continuous phase
d dispersed phase
i number of stage

Superscripts

j number of size fraction

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