COUNTERCURRENT PULSED AND RECIPROCATING PLATE EXTRACTORS. PREDICTION OF SAUTER MEAN DROP DIAMETER

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Six published correlations for Sauter diameter d_{32} in pulsed and reciprocating plate columns are compared with drop size measurements from seven different data sources. The correlation of Kumar and Hartland gives the best fit of data in the whole range of agitation rates. Also the semiempiric equations of Míšek and of Boyadzhiev and Spassov are of general validity at higher agitation levels. A new semiempiric equation covering the whole range of agitation rates and describing experimental data with a standard deviation of 10% is presented.

From the great variety of column types for liquid–liquid extraction, the reciprocating plate and pulsed plate columns were chosen for this investigation, which are known as simple, reliable and efficient apparatuses. Both types of columns are agitated by a perodic flow of dispersion through the plate openings. Contrary to the pulsed columns with a pulsed liquid flowing through the stationary plates, reciprocating plates mounted on a shaft attached by means of a yoke to a motor are used in the second type of columns. Column capacity and mass transfer rate can be controlled in a wide range by the rate of agitation which determines drop size.

The aim of calculation of column extractor is usually either to design a new extractor or to optimize the process of extraction in a working column. Both cases lead to the task to determine the conditions under which a required concentration of solute in the raffinate is obtained. At first, drop size d, its terminal velocity u_t and characteristic velocity u_0 are determined. Holdup of the dispersed phase X follows from u_0. Specific interfacial area a_0 is calculated from holdup and drop diameter. The rate of extraction is proportional to the product of a_0 and mass transfer coefficient K_d, which together with the coefficients of axial dispersion E determines the profile of solute concentration in both phases including the outlet concentrations.

This procedure of calculation is called "poelementnyi podchod" in Russian literature[1]. Reissinger and Marr[2] incorporated procedure in an iterative cycle which calculates the height of column necessary to reach the required outlet concentration. The procedure is not as simple and straightforward as the calculation of concentra-

tion profiles based on the height of transfer unit or the height equivalent to theoretical stage. However, to determine properly the effect of column geometry on the outlet solute concentration, the calculation of hydrodynamic characteristics $d \to \ldots$ $\ldots \to a_0$ cannot be avoided.

The first step is to calculate drop diameter d. The dispersed phase formed in the distributor enters the column with a drop size distribution depending on the geometry of distributor and on the flow rate of dispersed phase. Inside the agitated column these drops undergo repeatedly breakage and coalescence. Dynamic equilibrium between breakage and coalescence developes in a sufficient distance from the distributor, with a drop size distribution depending on the conditions inside the column only. The rate of establishing dynamic equilibrium depends on the coalescence ability of dispersion and on the intensity of agitation. The steady drop size distribution was found already in the distance of 3 to 4 plates from distributor in the work by Míšek[3]. In other cases, drops continued diminishing behind the twentieth plate[4] and even behind the fortieth plate[5]. Prabhakar et al.[6] measured the drop size distribution behind the 3rd, 10th and 16th plate of a column with relatively fast coalescing dispersion and found a gradual diminishing of drops along the column at low level of agitation contrary to higher agitation intensities where the steady drop size was reached already behind the 3rd plate.

A typical steady drop size distribution in the column is shown in Fig. 1. Mean drop size is defined as

$$d_{pq} = \sum_{j=1}^{M} n_j d_j^p \bigg/ \sum_{j=1}^{M} n_j d_j^q , \qquad (1)$$

where n_j is number of drops in the size fraction of drop diameter d_j.
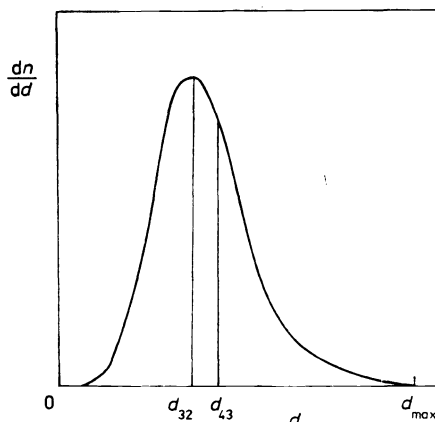

FIG. 1

Schematic representation of drop size distribution

Mean drop sizes d_{32} and d_{43} are most important in modelling of column extractors. To calculate the specific interfacial area, Sauter diameter is used:

$$a_0 = \sum_{j=1}^{M} n_j \pi d_j^2 , \tag{2}$$

$$X = \sum_{j=1}^{M} n_j (\pi/6) \, d_j^3 , \tag{3}$$

and Eqs (2), (3) result in

$$a_0 = 6X/d_{32} . \tag{4}$$

As Míšek[7] derived, mean diameter d_{43} should be used to calculate the holdup. Indicating the holdup and superficial velocity of the j-th size fraction X_j, resp. U_{dj}, we may write

$$X = \sum_{j=1}^{M} X_j , \quad U_d = \sum_{j=1}^{M} U_{dj} . \tag{5}$$

Hydrodynamic equation of countercurrent flow

$$u_0 \Phi(X) \, X = U_d + U_c X/(1-X) \tag{6}$$

is fulfilled also for the individual size fractions,

$$\left(u_{tj}/k_{ut}\right) \Phi(X) \, X_j = U_{dj} + U_c X_j/(1-X) , \quad j = 1, 2, ..., M . \tag{7}$$

Under conditions usual in the agitated column extractors, terminal velocity of drops is in transitional region and is approximately proportional to the drop diameter,

$$u_{tj} = p_3 d_j . \tag{8}$$

Summation of Eqs (7) gives

$$\left[\Phi(X)/k_{ut}\right] \sum_{j=1}^{M} u_{tj} X_j = U_d + U_c X/(1-X) \tag{9}$$

and after comparison of Eq. (9) with Eqs (3), (6), (8) we obtain

$$u_0 = \frac{1}{k_{ut}} \sum_{j=1}^{M} u_{tj} X_j / X = \frac{p_3}{k_{ut}} \sum_{j=1}^{M} n_j (\pi/6) \, d_j^4 / \sum_{j=1}^{M} n_j (\pi/6) \, d_j^3 = \frac{p_3}{k_{ut}} d_{43} . \tag{10}$$

CORRELATIONS FOR d_{32}

Many articles concerning the dependence of Sauter diameter on the conditions in pulsed or reciprocating plate columns appear in the literature. Correlations for d_{32} can be divided into two groups according to the intensity of agitation. Though the following survey is not complete, it shows the typical results in both groups.

High Agitation Level

Relations for d_{32} under these conditions are semiempiric and are based on the description of droplet breakup by turbulent eddies formed by periodic motion of plates or liquid. Assuming that the surface energy hindering the splitting of the maximum stable drop is equal to the kinetic energy of turbulent eddies of the droplet size, Hinze[8] and Shinnar and Church[9] derived

$$d_{\lim} = K(\sigma/\varrho)^{0.6}\, \varepsilon^{-0.4}\,. \tag{11}$$

Kinetic energy of turbulent eddy was derived from Kolmogorov theory of isotropic turbulence[10] in terms of the turbulent energy dissipation rate ε. Because of proportionality $d_{\lim} \sim d_{\max} \sim d_{32}$ we may write

$$d_{32} = k_1(\sigma/\varrho)^{0.6}\, \varepsilon^{-0.4}\,. \tag{12}$$

The rate of energy dissipation due to the flow of liquid through the plate openings in pulsed or reciprocating plate columns is calculated according to equations of flow through the orifice or according to the relations describing turbulent eddies. The first approach was applied by Jealous and Johnson[11] who derived the energy consumption in plate openings of a pulsed column

$$P = V\langle\varrho\rangle\,\varepsilon = \frac{S}{2}\,\frac{N(1 - \varepsilon_p^2)}{C_o^2\varepsilon_p^2}\,\langle\varrho\rangle\left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^3\,, \quad C_0 = 0.6\,, \tag{13}$$

where y is the position of pulsating liquid relative to plate. Eq. *(13)* was further adapted to a case of sinusoidal pulsation, which is completely defined by its amplitude and frequency. (The term "amplitude" is used ambiguously in the literature. In pulsed columns, amplitude denotes the stroke, while in reciprocating plate columns it is sometimes the stroke and sometimes its half, which is equal to the amplitude of sinusoidal wave. To compare the correlations describing both types of columns, the meaning amplitude = half stroke is used throughout this article.)

Thornton[12] proceeded similarly to Jealous and Johnson. Assuming a homogeneous

energy dissipation in the whole volume of column he wrote

$$\langle \varrho \rangle \, \varepsilon = \frac{1}{2} \frac{1 - \varepsilon_p^2}{C_o^2 \varepsilon_o^2 h} \langle \varrho \rangle \left(\frac{\mathrm{d}y}{\mathrm{d}t} \right)^2 \left| \frac{\mathrm{d}y}{\mathrm{d}t} \right| , \quad C_o = 0 \cdot 6 . \tag{14}$$

He pointed out that the maximum velocity of periodic motion controled the breakage of drops and showed examples of pulsation shapes where maximum velocity did not change with the amplitude and frequency in a certain range. However, the calculation of energy dissipation rate in a column with sinusoidal pulation was based on the mean values of $(\mathrm{d}y/\mathrm{d}t)^2$, $\mathrm{d}y/\mathrm{d}t$:

$$\langle \varrho \rangle \, \varepsilon = \frac{\pi^2}{2} \frac{1 - \varepsilon_p^2}{C_o^2 \varepsilon_p^2 h} \langle \varrho \rangle \, (2af)^3 , \quad C_0 = 0 \cdot 6 . \tag{15}$$

As $\mathrm{d}y/\mathrm{d}t$ is only a maximum for an infinitely short period of time during sinusoidal motion, Thornton did not consider the maximum as a sound basis for calculation of energy which determines drop splitting.

An analysis of dynamic effects in reciprocating plate and pulsed columns was published by Hafez and Procházka[13]. Their measurements of orifice coefficient for the plates with small openings (with diameter of openings comparable to the plate thickness) gave values of C_o in the range of $0 \cdot 6 - 0 \cdot 9$, dependent on Reynolds number. Baird et al.[5,14] calculated the rate of energy dissipation in Karr columns as

$$\langle \varrho \rangle \, \varepsilon = \frac{2\pi^2}{3} \frac{1 - \varepsilon_p^2}{C_o^2 \varepsilon_p^2 h} \langle \varrho \rangle \, (2af)^3 , \quad C_o = 0 \cdot 7 . \tag{16}$$

Eqs (15), (16) are numerically almost identical. In the work of Hafez and Baird[15] describing experiments in a Karr column with a sinusoidal motion of plates, the rate of energy dissipation according to Eq. (16) was multiplied by term $(1 + f_o)$, where the corrective coefficient f_o grows with frequency and diminishes with amplitude. Values of orifice coefficient were $C_o = 0 \cdot 56$ for $d_h = 0 \cdot 0143$ m and $C_o = 0 \cdot 57$ for $d_h = 0 \cdot 0075$ m.

Kostanjan et al.[16] correlated their results of measurement of power consumption in reciprocating plate columns with three types of plates (KRIMZ, GIAP and segmental sieve plates) by an equation

$$\varepsilon = 2 \cdot 5 \, (2af)^3 \, d_h / \varepsilon_p^2 \delta h . \tag{17}$$

Using the second approach, the rate of energy dissipation is derived from the ma-

ximum drop velocity u_L and from the scale of turbulence L,

$$\varepsilon = u_L^3/L. \tag{18}$$

Míšek[3] equated u_L to the maximum velocity in plate openings $(k_2 2af + U_c)/\varepsilon_p$, where $k_2 = \pi$ for sinusoidal motion. Coefficient k_2 rises in pulsed columns where the motion induced by pulsator is less smooth. Míšek evaluated $k_2 = 5\cdot1$ for the pulsator used in his experiments. He chose the diameter of plate openings as the scale of turbulence. To reach a better agreement of model with experimental results, velocity u_L was multiplied by $\varepsilon_p^{0\cdot75}$ with a final result

$$\varepsilon \sim (k_2\, 2af + U_c)^3/\varepsilon_p^{0\cdot75} d_h. \tag{19}$$

Boyadzhiev and Spassov[17] put u_L equal to the mean velocity of liquid flowing through the plate openings during a half of period $4af/\varepsilon_p$ and L equal to the radius of plate openings, and related the energy dissipated in the openings to the whole cross section of column multiplying it by ε_p,

$$\varepsilon \sim (4af)^3/d_h \varepsilon_p^2. \tag{20}$$

After substitution of expressions for ε into Eq. (12) and evaluation of coefficient k_1 from experimental data, correlations for d_{32} were obtained by Míšek[3], Baird and Lane[5] and Boyadzhiev and Spassov[17], given in Table I. The last authors used a criterion e_m to impose limitation on the range of agitation. To extend the range of correlation validity to lower agitation level, Baird and Lane[5] included gravitational power dissipation per unit volume ψ_2 into the equation. However, the result was not satisfactory. The authors assumed that a term describing the splitting due to collisions of drops with the plate would be necessary to improve further the agreement between the model and experiments. Correlation of Kostanyan et al.[16] does not contain interfacial tension, as they measured only with one system of liquids. Correlation of Maksimenko[18] is fully empiric. The common characteristic of all five correlations for d_{32} at high level of agitation is the value of exponent at amplitude and frequency, which is close or equal to $-1\cdot2$.

Low Agitation Level

As the turbulence is not fully developed at mild agitation, its effect on drop breakage is comparable to the effect of other phenomena: collisions of droplets with plates, shear forces on larger drops moving through the plate openings, shear forces during gravitational flow of drops between plates. Therefore the dependence of d_{32} on the amplitude and frequency of periodic motion is weaker than at intensive agitation. The rate of approaching the stable size of drops is lower and the changes of drop

diameter along the column are pronounced. Correlations for d_{32} contain the number of plates between the dispersed phase inlet and the locus of measurement as parameter. Table I shows three empiric correlations for these conditions: equations of Kagan et al.[19], Assenov and Penchev[20] and Reissinger and Marr[2]. The last cor-

TABLE I

Correlations for d_{32}

Reference	Correlation	Column
3	$d_{32} = 0.439(\sigma/\varrho_c)^{0.6}\,\varepsilon_p^{0.3}d_h^{0.4}(k_2\,2af + U_c)^{-1.2}$ $k_2 = \pi$ for sine wave-form, $k_2 = 5.1$ for the pulsator employed	pulsed
5	$d_{32} = 0.357\sigma^{0.6}/\varrho_c^{0.2}(\psi_1 + \psi_2)^{0.4}$ $\psi_1 = (2\pi^2/3)\,[(1 - \varepsilon_p^2)/hC_o^2\varepsilon_p^2)]\,\langle\varrho\rangle\,(2af)^3,\ C_o = 0.7$ $\psi_2 = g\,\Delta\varrho[U_d + XU_c/(1 - X)]$	reciprocating (Karr)
18	$d'_{32} = 0.272(\sigma/\varrho_c)^{0.5}\,(\varrho_c/\Delta\varrho)^{0.34}\,d_h^{0.5}\varepsilon_p(g/2af^2)^{0.12}\,(2af)^{-1}$ $d_{32} = d'_{32}(1 + 0.3X)$	reciprocating
17	$d_{32} = 0.57(\sigma/\varrho_c)^{0.6}\,d_h^{0.4}\varepsilon_p^{0.8}(4af)^{-1.2}$ for $e_m = \varrho_c(4af)^3/2\varepsilon_p^2 > 0.48$ kg s^{-3}	reciprocating + pulsed
16	$d_{32} = C_1\langle\varrho\rangle^{-0.4}\varepsilon_p^{0.8}(h\delta/d_h)^{0.4}\,(2af)^{-1.2}$ $C_1 = 5.6 \cdot 10^{-3}$ for kerosene(d)–water(c)	reciprocating
19	$d_{32} = 0.92(\sigma/g\varrho_c)^{0.5}\,(\mu_c g/\varrho_c)^{0.1}\,(2af)^{-0.3}\,N^{-0.11}$ for $\varepsilon_p = 0.082,\ d_h = 0.002$ m, $h = 0.05$ m	pulsed
20	$d_{32} = 0.01(\sigma^2/\Delta\varrho g\mu_c)^{0.5}\,(2af)^{-0.5}\,N^{-0.1}$ for $\varepsilon_p = 0.23,\ h = 0.05$ m	pulsed
2	$d_{32} = 0.20(\sigma/g\,\Delta\varrho)^{0.5}\,(2af\mu_c/\sigma)^{-0.3}\,N^{-0.1}(d_h\varrho_c\sigma/\mu_c^2)^{0.33}$ $(\mu_c^4 g/\Delta\varrho\sigma^3)^{0.23}\,(\sigma_{Kopf}/\sigma_{Sumpf})^{0.6}$, for $0.008 < 2af < 0.031$ m s^{-1}	pulsed
21	$d_{32} = 9.71 \cdot 10^{-4}h^{0.11}(2af/\varepsilon_p^{0.66})^{-0.34}$ for $2af/\varepsilon_p^{0.66} < 0.09$ m s^{-1} $d_{32} = 9.16 \cdot 10^{-5}(2af/\varepsilon_p^{0.66})^{-1.2}$ for $2af/\varepsilon_p^{0.66} \geqq 0.09$ m s^{-1}	reciprocating
22	$d_{32} = 1.35\varepsilon_p^{0.4}(\sigma/\Delta\varrho g)^{0.5}\,[h/(\sigma_*/\varrho_* g)^{0.5}]^{0.18}$ $[\mu_d(g/\varrho_*\sigma^3)^{0.25}]^{0.14}$ $(\sigma/\sigma_*)^{0.06}\,[0.23 + \exp(-29.66 \cdot 2af^2/g\varepsilon_p)]$ $\varrho_* = 998.21$ kg m^{-3}, $\sigma_* = 0.07275$ N m^{-1}	pulsed
this work	$d_{32} = 1/[1/(d'_{32})^2 + 1/(0.81\sigma/\Delta\varrho g) + 1/d_h^2]^{0.5}$ $d'_{32} = 0.116(\sigma/\varrho_c)^{0.6}\,[\varepsilon_p^2 z/(1 - \varepsilon_p^2)]^{0.4}\,I^{-1.2}$ $I = k_3 a^{0.9}f^{1.1},\ k_3 = 1$ (m s)$^{0.1}$ for sine wave-form $k_3 = 1.5$ (m s)$^{0.1}$ for pulsed columns $z = \min\{0.17\varepsilon_q^{-0.33}I^{0.5}; h\}$	reciprocating + pulsed

relation includes also the direction of mass transfer — the form given in Table I describes the extraction from continuous phase to the lighter dispersed phase, with "Kopf", "Sumpf" relating to the head, resp. bottom of column.

Whole Range of Agitation Rates

Němeček and Procházka[21] evaluated drop sizes measured in reciprocating plate column with sieve plates. As the intensity of reciprocation varied in a wide range, a break separating two regions of agitation could be observed on the graph of dependence of d_{32} on $2af$. Intensity of agitation in the point of break was 1·8 times higher than according to the criterion e_m in correlation of Boyadzhiev and Spassov[17].

Kumar and Hartland[22] correlated the values of d_{32} collected from twelve sources by an equation valid in the whole range of agitation intensities, including the conditions with no agitation. They reached a mean deviation of 11%. A term $2af^2$ proportional to the acceleration of periodic motion was used to describe the influence of agitation on d_{32}, instead of the term $2af$ proportional to the velocity of motion. This agrees with observations made both in pulsed plate columns and in reciprocating plate columns driven by motor with a yoke, that frequency affects the column behaviour more than amplitude of periodic motion. For example, Sege and Woodfield[23] determined a dependence of flooding point in a pulsed column on term $2af^n$, where $1 < n < 2$. Sauter diameter in reciprocating plate column measured by Assenov et al.[24] correlated better with term $2af^2$ than with $2af$. Khemangkorn et al.[4] evaluated d_{32} measured in an intensively pulsed sieve plate column as proportional to $(2a)^{-1} f^{-1·24}$. Similar exponents at a, f are also in the correlation of Maksimenko[18].

New Correlation for d_{32}

A new correlation based both on published data and correlations and on the measurements performed in our laboratory in reciprocating plate columns driven by a motor with yoke (Heyberger et al.[25], Jiřičný[26]) was developed. The correlation

$$d_{32} = 1/[1/(k_4\sigma/\Delta\varrho g) + 1/d_h^2 + 1/(d'_{32})^2]^{0.5}, \quad k_4 = 0·81 \qquad (21)$$

combines the effects of (i) drop breakup by collision with plate, growing with the density difference of phases and diminishing with interfacial tension, (ii) breakup by shear in the openings of diameter d_h and (iii) breakup by periodic motion, which limits the Sauter mean diameter to d'_{32}. Correlation holds in the whole range of agitation intensities.

The intensity of agitation is described by expression

$$I = I[a, f, y(t)], \qquad (22)$$

which depends on the form of periodic motion $y(t)$. Especially for the sine wave--form, an expression is used[27]

$$I = k_3 a^{0.9} f^{1.1}, \quad k_3 = 1 \, (\text{m s})^{0.1}. \tag{23}$$

The type of pulsator is decisive for d_{32} and I in pulsed plate columns. On the average, the data measured in pulsed columns correlate with intensity of agitation according to Eq. (23) and $k_3 = 1.5 \, (\text{m s})^{0.1}$.

Turbulent eddies initiated by periodic motion do not cover the whole distance between plates at low intensities of agitation. They form a zone around the plates, the height of which grows with square root of agitation intensity, according to measurements in Karr column performed by Vohradský[28]. Combining these results with heights of agitated zone on sieve plates measured by Němeček and Procházka[21] we obtain

$$z = \min \{ 0.17 \varepsilon_q^{-0.33} I^{0.5}; h \}. \tag{24}$$

Maximum height of zone is equal to the plate distance h.

Rate of energy dissipation is calculated from Eq. (16) with $C_o = 0.6$ and with the height of region of dissipation equal to z,

$$\varepsilon = 18.3 I^3 (1 - \varepsilon_p^2) / \varepsilon_p^2 z. \tag{25}$$

Sauter diameter d'_{32} resulting from agitation is calculated using Eq. (12),

$$d'_{32} = k_1 (\sigma/\varrho_c)^{0.6} \varepsilon^{-0.4}, \quad k_1 = 0.37 \tag{26}$$

with constant k_1 evaluated by comparison of Eq. (21) with experiments.

Symbols ε_q, ε_p in Eqs (24), (25) denote the effective free areas of plates. They differ only for the VPE plates, which are equipped with two types of perforations — smaller ones of diameter d_h and fractional free area ε_d and larger ones with overflows of fractional free area ε_c. Comparison of model with values of d_{32} measured on these plates led to formulas $e_q = e_d + \varepsilon_c$, $\varepsilon_p = \varepsilon_d / (1 - \varepsilon_c)$.

COMPARISON OF CORRELATIONS WITH EXPERIMENTAL DATA

The correlations given in Table I are based on the process of drop splitting in a column of given geometry and intensity of agitation. They take into account neither the influence of drop size distributor nor the rate of drop coalescence. (Only Maksimenko[18] describes a drop enlargement from d'_{32} to d_{32} as a result of coalescence. Validity of this expression is, however, limited, as it contains no measure of drop coalescence ability.) These correlations should therefore describe d_{32} in a dispersion with slow

coalescence which affects the drop size to a negligible extent, and after passage of drops through a sufficient number of plates, where d_{32} depends no more on the original size of drops at the distributor.

The authors of most correlations quoted in Table I evaluated their own measurements only and did not investigate the predictive ability of used relations by comparison with other published data. This was done only by Boyadzhiev and Spassov[17] who established the accuracy of their correlation within 20%, and — with other sets of data — by Kumar and Hartland[22] who reached an average deviation of 11%, while the deviation of correlation of Boyadzhiev and Spassov[17] grew to 35% for these sets of data.

To judge the reliability of correlations, sets of data given in Table II were used in this work. Some of available data, namely those measured too close to the distributor of dispersed phase (less than 8 plates apart) and those with higher range of coalescence, distinguishable e.g. by growth of d_{32} with flow rate of dispersed phase, were not included.

Knowledge of amplitude and frequency in addition to their product is necessary in some correlations. As only this product was indicated by Baird and Lane[5] for set A, we made an assumption $a = 0.0135$ m after comparison with other publications from the same laboratory.

Results are shown in Table III. Those of correlations from Table I which are based on one liquid system or on one column geometry are obviously of no general applicability and therefore were excluded from comparison. The first four correlations for intensive agitation were compared only with the data fulfilling condition $e_m > 0.48$ kg/s³; correlation of Reissinger and Marr[2] was compared with the data measured in prescribed range of agitation and only the last two correlations were compared with all experimental data from Table II.

As most literary sources did not contain information on flow rates and on holdup of dispersed phase, the superficial velocity in Míšek's correlation[3] was taken $U_c = = 0.002$ m/s and the energy consumption ψ_2 in correlation of Baird and Lane[5] was omitted. These simplifications affect negligibly the calculated d_{32} at high agitation rates. Coefficient $k_2 = \pi$ was used in Míšek's correlation[3] for all data sets. Correlation of Maksimenko[18] was calculated with $X = 0$, that means without correction on drop coalescence.

Calculated drop diameters d_{32C} are compared with measured ones d_{32M} according to two criteria. The ratio

$$\langle d_{32C}/d_{32M} \rangle = \frac{1}{n} \sum_{i=1}^{n} d_{32C,i}/d_{32M,i} \tag{27}$$

on the left hand side of Table III indicates whether the correlation gives too large

TABLE II
d_{32} — Experimental data

Set of data	Ref.	Column	Geometry			Liquid properties				Agitation
			ε_p —	d_h mm	h mm	ϱ_c kg m^{-3}	ϱ_d kg m^{-3}	μ_c g m^{-1} . s^{-1}	σ mN m^{-1}	$2af$ mm s^{-1}
A	5	reciprocating (Karr)	0·55	12·7	28·6	805 816	1 000 1 000	1·07 0·83	28·2 8·7	0—63 0—27
B	26	reciprocating (Karr)	0·383	12·0	74·5	997	1 246	0·88	28	35—45
C	25	reciprocating (VPE)	0·124	3·0	100	997	871	0·95	36	8—16
D	29	reciprocating	0·044— 0·192	2·5— 3·6	50— 150	1 000	1 460	0·93	32	3·6—58
E	17	pulsed	0·198	2·0	50	1 000	1 180	1·0	34	15—36
F	4	pulsed	0·188	2·0	50	1 000	1 590	1·0	45	30—60
G	30	pulsed	0·190	3·0	30— 70	1 000	796	1·0	10	5—44

TABLE III

Comparison of correlations for d_{32} with experimental data (correlations: *1* Mišek[3], *2* Baird and Lane[5], *3* Maksimenko[18], *4* Boyadzhiev and Spassov[17], *5* Reissinger and Marr[4], *6* Kumar and Hartland[22], *7* this work)

Set of data	$\langle d_{32C}/d_{32M}\rangle$								$s, \%$						
	1	*2*	*3*	*4*	*5*	*6*	*7*	$\langle 1\text{--}7\rangle$	*1*	*2*	*3*	*4*	*5*	*6*	*7*
A	0·75	1·02	3·44	1·26	1·14	1·02	1·02	1·38	26	6	245	27	21	15	8
B	0·86	1·37	2·83	1·22	—	0·85	0·93	1·34	14	37	184	23	—	16	8
C	1·09	1·86	1·69	0·89	2·11	0·84	0·89	1·34	10	86	69	11	113	19	11
D	0·86	1·14	0·61	0·54	1·00	0·31	0·71	0·74	29	29	41	47	33	70	30
E	1·27	2·43	2·46	1·30	2·78	1·84	1·31	1·91	28	143	146	30	181	89	33
F	0·95	1·73	1·19	0·93	1·04	0·95	1·05	1·12	11	75	22	12	10	11	12
G	1·05	1·61	2·18	1·04	2·30	0·98	0·94	1·44	18	62	123	18	137	16	9
A—C, F, G	0·94	1·52	2·27	1·07	1·65	0·93	0·97	—	17	60	151	19	90	14	10

or too low values of d_{32}. Relative standard deviations

$$s = 100 \left\{ \frac{1}{n} \sum_{i=1}^{n} [(d_{32\mathrm{C},i}/d_{32\mathrm{M},i}) - 1]^2 \right\}^{0.5} \tag{28}$$

are given on the right hand side.

Average values of $\langle d_{32\mathrm{C}}/d_{32\mathrm{M}} \rangle$ from the columns $1-7$ enable us to make a comparison of sets of data based on mean values from the correlations. They are written under the heading $\langle 1-7 \rangle$. A large deviation shows set D with measured drop sizes exceeding the prediction, and set E where a converse situation occurs. As the height of column in Němeček's experiments[29] was only 1·2 m, the steady drop size distribution might not yet been developed at the point of measurement inside the column. It is also possible that these drops were enlarged by coalescence. Drop diameters measured by Boyadzhiev and Spassov[17] were too small even when compared with the correlation developed by these authors. The reason might be a jerky motion of pulsator causing an increase of maximum velocity of liquid through the plate openings and thus accelerating drop breakage.

With these two sets of data left off, the overall mean ratios $\langle d_{32\mathrm{C}}/d_{32\mathrm{M}} \rangle$ and standard deviations for individual correlations were calculated. These values given in the last line of Table III characterize the overall agreement of correlations with experimental results. The best agreement was reached with new correlation (No. 7) and with correlation of Kumar and Hartland (No. 6). A good agreement at high agitation level was also obtained using correlations of Míšek (No. 1) and of Boyadzhiev and Spassov (No. 4), which coincide at $\varepsilon_p = 0{\cdot}20$. The other correlations investigated are of limited validity.

Several sets of data together with curves of correlations are shown in Figs $2-6$.
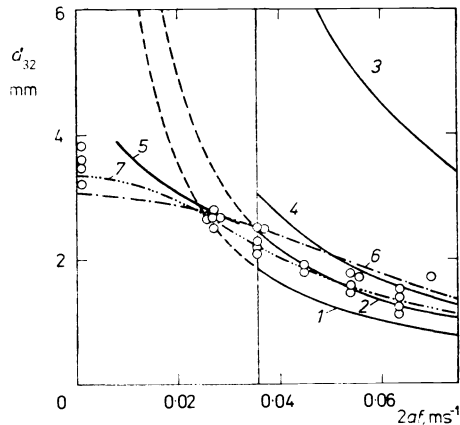

FIG. 2

Comparison of correlations numbered according to Table III with data of Baird and Lane[5]. Water dispersed in kerosene
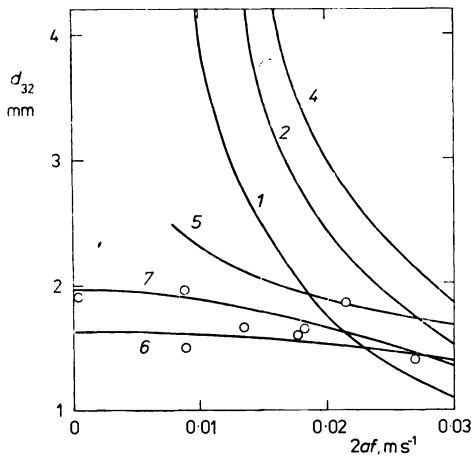
FIG. 3

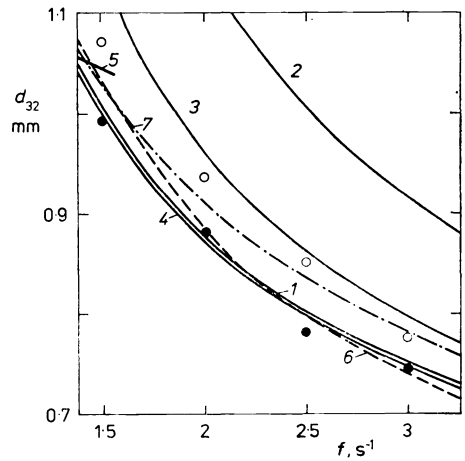Comparison of correlations with data of Baird and Lane[5]. Water dispersed in methyl-isobutylketone

FIG. 4

Comparison of correlations with data of Khemangkorn et al.[4], $a = 0\cdot010$ m. Direction of solute transfer: $\circ$ $c \to d$, $\bullet$ $d \to c$
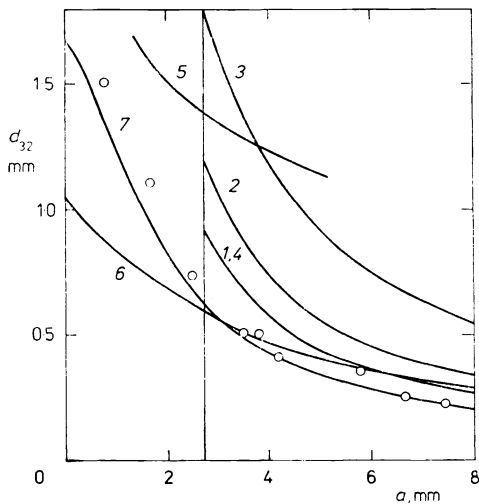

FIG. 5

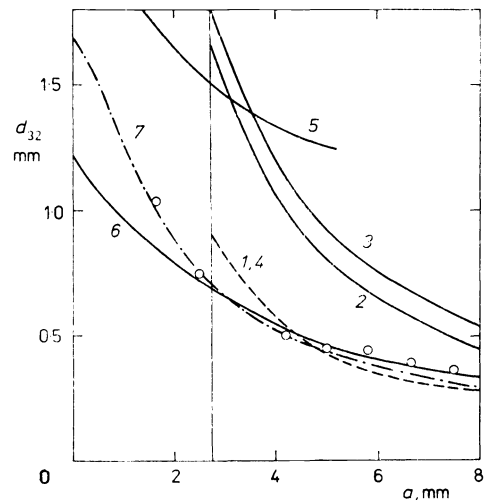Comparison of correlations with data of Miyauchi and Oya[30]. $f = 3$ Hz, $h = 0\cdot03$ m

FIG. 6

Comparison of correlations with data of Miyauchi and Oya[30]. $f = 3$ Hz, $h = 0\cdot07$ m

The region of intensive agitation according to the criterion $e_m > 0.48$ kg/s^3 is separated by a vertical line; Fig. 3 covers only the region of mild agitation contrary to Fig. 4 which is completely in the range of intensive agitation.

As Boyadzhiev and Spassov[17] pointed out, some other effects not included in correlations for d_{32} should also be taken into account. The effects of drop coalescence, of drop size development along the column and of the shape of periodic motion have been mentioned above. Another well known phenomenon is the effect of mass transfer direction. Interfacial tension decreases with solute concentration in most liquid systems; mass transfer from drops to continuous phase then facilitates and extraction in the opposite direction hinders drop coalescence. As follows from data of Khemangkorn et al.[4] measured in a system without coalescence, drop breakage is also affected by mass transfer, though in a lower degree.

Wetting of plates by dispersed phase is also of great importance. This phenomenon is undesirable in column extractors, as extremely large drops tearing off from the wetted plates form a nonhomogeneous dispersion with small interfacial area and slow mass transfer. Size of these drops is obviously not described by correlations developed for conditions of slow coalescence.

Influence of surfactants on drop breakup was studied by Koshy, Das and Kumar[31]. In the presence of surfactants, drop sizes diminish to greater extent than corresponds to the decrease of interfacial tension. The authors explained how the gradient of interfacial tension developed after droplet deformation contributes to splitting of droplet and described this phenomenon quantitatively. A similar quantitative description of other phenomena affecting drop breakage and coalescence as mentioned above would extend the applicability of correlations for d_{32} and improve their reliability in practice.

CONCLUSION

The proposed correlation for Sauter diameter describes selected experimental data with a standard deviation of 10%, which is a better result than with correlations published earlier. The main difference between d_{32} calculated according to the new correlation and according to correlation of Kumar and Hartland[22], the best of previous correlations, is at very low rates of agitation where the new correlation takes into account the size of plate perforations. Both correlations can be recommended for prediction of d_{32} in the whole range of agitation rates.

However, the results obtained from correlations should be corrected in certain cases: at higher rates of drop coalescence, close to the dispersed phase inlet and at higher concentrations of surfactants. New correlation can be adapted to columns with non-sinusoidal pulsation/reciprocation by changes in the expression for effective intensity of agitation.

SYMBOLS

a amplitude (half stroke) of reciprocation/pulsation, m

a_0 specific interfacial area, m^{-1}

c concentration of solute, $kmol\ m^{-3}$

C_0 orifice coefficient

d drop diameter, m

d_{32} Sauter mean drop diameter, m

d'_{32} Sauter diameter resulting from drop break-up by reciprocation/pulsation, m

d_{lim} maximum stable drop diameter, m

d_{max} maximum drop diameter, m

d_h diameter of plate openings, m

e_m criterion of agitation level, $kg\ s^{-3}$

E coefficient of axial dispersion, $m^2\ s^{-1}$

f frequency of reciprocation/pulsation, s^{-1}

g gravitational acceleration, $m\ s^{-2}$

h spacing between plates, m

k_1 constant in Eqs (12), (26)

k_2 parameter of reciprocation/pulsation efficiency in Míšek's model

k_3 parameter of reciprocation/pulsation efficiency in new correlation, $(m\ s)^{0.1}$

k_4 constant in Eq. (21)

$k_{ut} = u_t/u_0$, parameter

K_d mass transfer coefficient, $m\ s^{-1}$

M number of size fractions

n number of measurements

n number of drops per unit volume, m^{-3}

$p_3 = u_t/d$, constant, s^{-1}

P power consumption due to frictional forces in plate openings, $kgm^2\ s^{-3}$

s standard deviation, %

S column cross-section, m^2

t time, s

u_0 characteristic velocity, $m\ s^{-1}$

u_t terminal velocity, $m\ s^{-1}$

U superficial velocity of phase, $m\ s^{-1}$

V column volume, m^3

X holdup of dispersed phase (volume fraction)

y vertical coordinate, m

z height of breakage zone, m

$\Delta\varrho$ density difference between phases, $kg\ m^{-3}$

δ plate thickness, m

ε rate of energy dissipation per unit mass, $m^2\ s^{-3}$

ε_d fractional free area of plate

ε_c fractional free area of openings with overflows in VPE plates

$\varepsilon_p, \varepsilon_q$ effective free areas of plate ($\varepsilon_p = \varepsilon_q = \varepsilon_d$ for plates without overflows)

$\Phi(X)$ function in Eq. (6); $\lim\limits_{X \to 0} \Phi(X) = 1$

μ viscosity, $kg\ m^{-1}\ s^{-1}$

ϱ density, $kg\ m^{-3}$

$\langle\varrho\rangle$ mean density of dispersion, $kg\ m^{-3}$

σ interfacial tension, $N\ m^{-1}$

Subscripts

c	continuous phase
d	dispersed phase
j	number of size fraction
C	calculated
M	measured

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Translated by the author.