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Axial Dispersion and Phase Holdup Characteristics in Reciprocating Plate Extraction Columns

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Abstract

Axial dispersion and phase holdup characteristics have been determined in a 0.102-m i.d. × 3.5 m high QVF glass column. The axial dispersion coefficient decreases with increasing reciprocating frequency (f) and amplitude (A) in the inhomogeneous dispersed phase flow regime, whereas it increases in the emulsion flow regime. The axial dispersion coefficient with a perforated plate increases with continuous and dispersed phase velocities. However, the effect of phase velocities on axial dispersion is less pronounced with the fan plate. The axial dispersion coefficient can be correlated with A^2f, fluid velocities, and the free fractional opening area of the plates. The dispersed phase holdup increases with an increase in agitation intensity, Af, and decreases with the free opening area of the plate.

INTRODUCTION

In recent years, reciprocating plate extraction columns have been widely used in pharmaceutical, petrochemical, metallurgical, and chemical processes because of their high extraction performance (*1*).

However, the reciprocating extraction column has high axial dispersion due to the turbulent eddies which are formed through the plate holes during plate reciprocation. Therefore, various plate or baffle geometries have

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been employed to reduce the axial dispersion. The semicircular plate (*2*), D-type perforated plate (*3*), typical doughnut baffle plate (*4, 5*), fan baffle plate (*6*), and D-shaped baffle plate (*7*) have been employed for reducing circulation effects in large-scale pulsed and reciprocating plate extraction columns.

Hafez et al. (*6*) and Yu and Kim (*7*) reported that axial dispersion can be reduced effectively by adding a baffle plate in the Karr-reciprocating plate and pulsed columns. However, studies on the effect of the free opening area of plates or baffles on the axial dispersion and phase holdup are very sparse.

Therefore, in this study the effect of the free opening areas of the fan and baffle plates, the reciprocating amplitude and the frequency on the axial dispersion coefficient (E) in the continuous phase, and the dispersed phase holdup have been determined.

EXPERIMENTAL

The reciprocating column was a standard 4-in. (10.2 cm) nominal diameter QVF glass column with an overall height of 3.5 m and a reciprocating plate stack about 1.8 m high (Fig. 1).

The reciprocating frequency and amplitude were varied with a speed-controlled dc motor (1 hp) with an adjustable yoke. The stainless steel square rod supporting the plate stack was attached to the adjustable yoke for plate reciprocation. Spacers were made of a 51-mm length of stainless steel pipe with an outside diameter of 18.5 mm. Two types of plate were employed with different arrangements: a perforated plate with nine holes of 22 mm diameter with an opening area fraction of 0.602, and a fan plate of 1 mm thickness with a different number of blades at an inclined angle of 30°.

Details of the plate arrangements are summarized in Table 1 and Fig. 2.

Tap water (0.005 N HCl + phenolphthalein) and kerosene were used as the continuous and dispersed phases, respectively. The properties of the liquids are summarized in Table 2.

The axial dispersion coefficient in the continuous phase was measured by the color change method developed by Kim and Baird (*8*) in which a single pulse of 1 N sodium hydroxide solution as a tracer was injected into the column through a doughnut-shaped distributor in which 10 holes of 1.5 mm diameter were drilled horizontally about 0.5 m below the distributor plate of the continuous phase (Fig. 1).

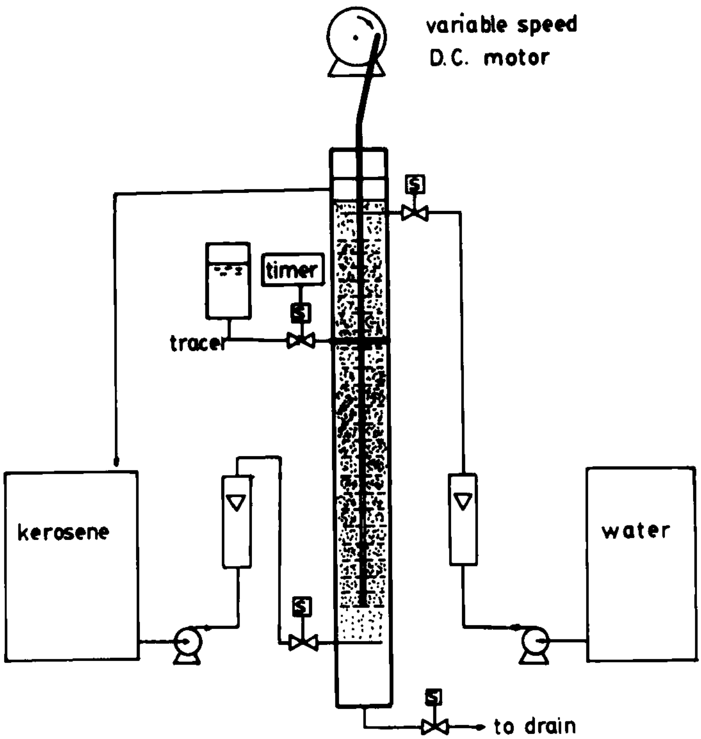

FIG. 1. Schematic diagram of experimental apparatus.

TABLE 1
Details of the Plate Arrangements

Arrangement	Number of blades or holes	Projected opening area fraction, σ	Remarks
1	9	0.602	Perforated plate
2	2	0.796	Fan plate—1
3	4	0.626	Fan plate—2
4	6	0.456	Fan plate—3
5	8	0.285	Fan plate—4
6	Fan plate 3 + perforated plate	0.608	Baffled arrangement

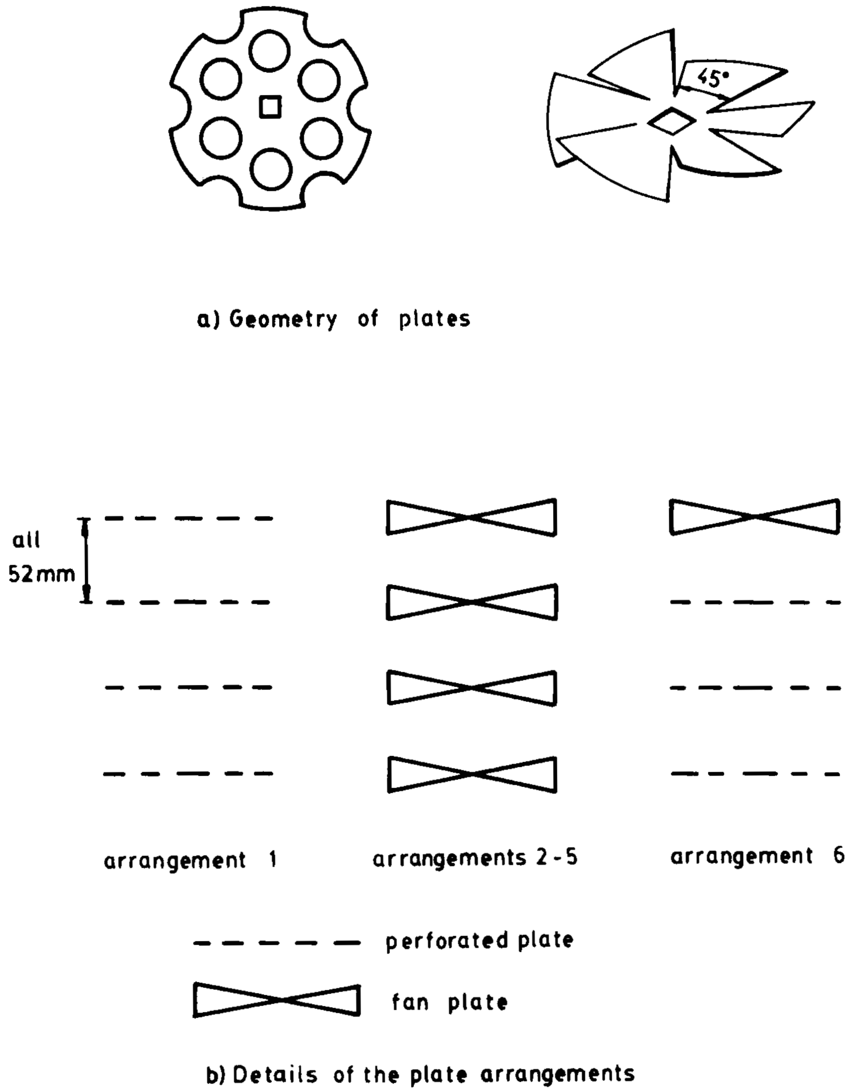

FIG. 2. Details of a) plate geometries and b) plate arrangements.

TABLE 2
Properties of Liquids[a]

Phase	Liquid	Density (kg/m^3)	Surface tension (mN/m)	Viscosity (mPa · s)
Continuous	Water	1000	72.0	1.0
Dispersed	Kerosene	785	27.0	1.67

[a]Interfacial tension: 20 mN/m.

The overall dispersed phase holdup was determined by shutting off the flows at the inlet and outlet lines by the use of solenoid valves and by allowing the dispersed phase droplets in the column to settle to the interface (*7*).

The effect of the free opening area of the fan plate (Arrangements 2 to 5) on E and the phase holdup were determined, and the results are compared with those in the conventional Karr column of Arrangements 1 and 6.

RESULTS AND DISCUSSION

Axial Dispersion Coefficient

Effect of Amplitude

The effect of the reciprocating amplitude on E with Arrangements 1, 3, and 6, which have similar free fractional opening areas of about 0.6, is shown in Fig. 3. As can be seen in Fig. 3(a) and 3(b), the axial dispersion coefficient has maximum peaks at a low amplitude of 1.27 cm and a frequency below 1.0 Hz. Similar results were observed in a 0.15-m i.d. reciprocating plate column (*6*), whereas many previous investigators (*7–10*) reported that the axial dispersion coefficient increases monotonously with an increase in amplitude. In addition, the amplitude may affect the eddy size during the reciprocation of plates in small columns (*8*) or in the small free opening area (*7, 9, 10*). However, axial dispersion in large columns could be caused by the vertical circulation flow which is induced by the transverse nonuniformity of velocity profile (*6, 7, 11*) in two-phase countercurrent flow systems at lower agitation intensity, Af. The axial dispersion coefficient decreases with an increase in amplitude in the range 1.27–2.54

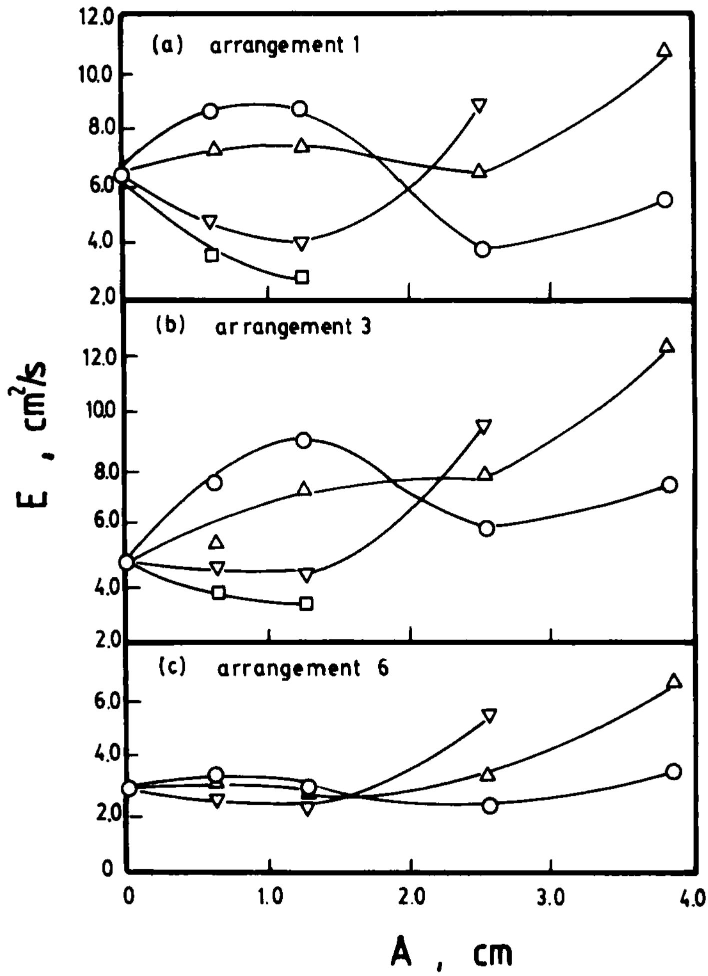

FIG. 3. Effect of amplitude and plate geometry on E at $U_c = U_d = 0.25$ cm/s. f = (○) 0.5, (Δ) 1.0, (∇) 2.0, (□) 3.0 Hz.

cm since the transverse nonuniformity of the velocity profile may decrease with droplet breakage at higher amplitudes whereas, as can be seen in Fig. 3(b), the axial dispersion coefficient of the fan plate having the same free opening area as the perforated plate also exhibits a maximum value at a lower amplitude, as in the case of the perforated plate only (Arrangement 1). Since the flow pattern is unchanged through a plate stack of the same shape at lower amplitude, the transverse nonuniformity of the velocity profile may not be reduced significantly by the plate configuration.

However, the axial dispersion coefficient does not exhibit a maximum value with Arrangement 6 at the lower agitation intensity in a 0.15-m i.d. column (Fig. 3c), as observed by Hafez et al. (*6*). Moreover, the axial dispersion with Arrangement 6 has lower values than Arrangements 1 and 3 at a higher agitation intensity. This may reflect the fact that the baffle plate prevents vertical circulation flow while it provides an increase in radial mixing during plate reciprocation (*6, 7, 12*).

The effect of amplitude on E with various free opening areas of the fan plates in Arrangements 2, 4, and 5 is shown in Fig. 4. With the smaller free opening areas of Arrangements 4 and 5, the amplitude may control the eddy size caused by the free opening area of plates, as reported by Yu and Kim (*7*). Therefore, the axial dispersion coefficient increases with an increase in amplitude except for Arrangement 2 which has a free fractional opening area of 0.796. As the free opening area is reduced, the rate of increase in E is less pronounced with an increase in amplitude since radial mixing increases due to the shape of the fan plate.

Effect of Frequency

The effect of frequency on E with Arrangements 1, 3, and 6 which have a similar free fractional opening area ($\sigma \simeq 0.6$) is shown in Fig. 5. In general, the reciprocation frequency may represent the number of the liquid circulation flow and the eddy velocity. As can be seen, the axial dispersion coefficient increases with an increase in frequency at amplitudes above 2.54 cm and decreases at amplitudes below 1.27 cm. At lower amplitudes ($A < 1.27$ cm), large droplets effectively disintegrate with an increase in frequency. The axial dispersion coefficient decreases with an increase in frequency due to drop size reduction in the maldistribution. However, at higher amplitudes ($A > 2.54$ cm), the flow regime changes from inhomogeneous flow to the emulsion regime in which the droplets have a homogeneous small size. Therefore, the axial dispersion coefficient in-

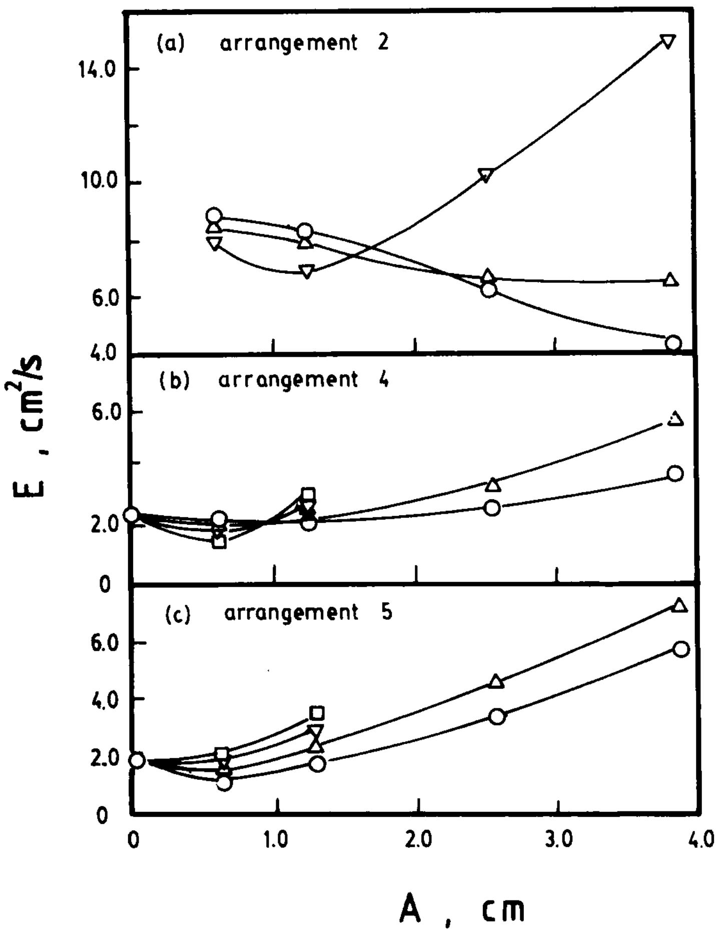

FIG. 4. Effect of amplitude on E with various free fractional opening areas of the fan plate at $U_c = U_d = 0.25$ cm/s. f = (○) 0.5, (△) 1.0, (▽) 2.0, (□) 3.0 Hz.

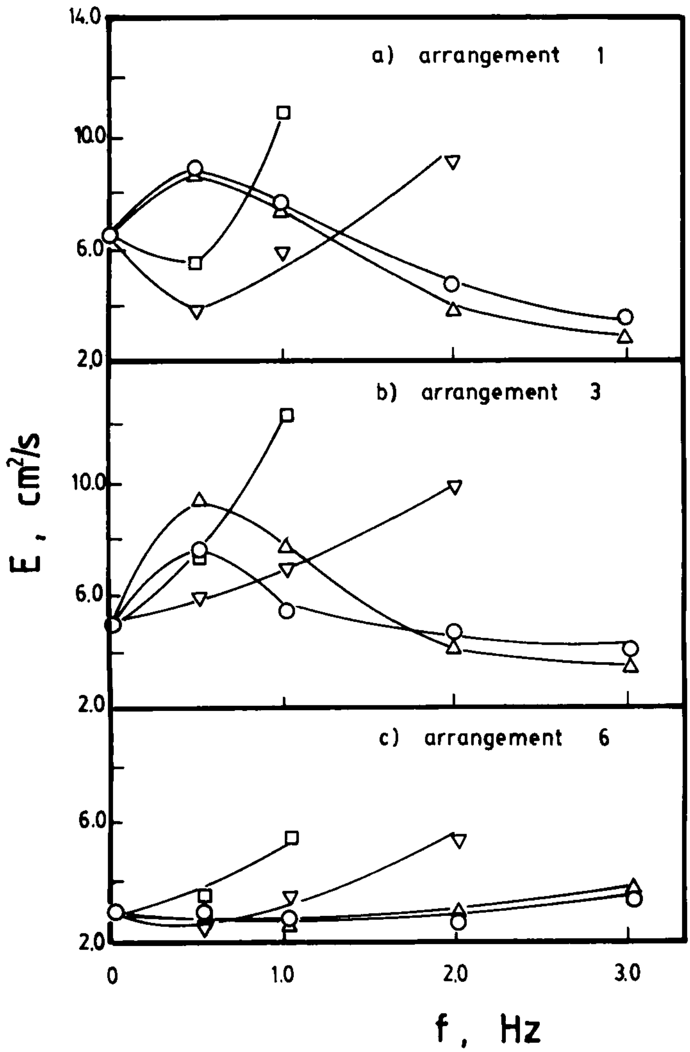

FIG. 5. Effect of frequency and plate geometry on E at $U_c = U_d = 0.25$ cm/s. A = (○) 0.635, (△) 1.27, (▽) 2.54, (□) 3.81 cm.

creases with an increase in frequency at higher amplitudes since the circulation velocity increases.

The effect of frequency on E with the various plate free opening areas of Arrangements 2, 4, and 5 is shown in Fig. 6. The axial dispersion coefficient increases linearly with an increase in frequency, as observed by previous investigators (*7–10*), except for Arrangement 2, which has a free fractional opening area of 0.796. As the free opening area is reduced, the droplets are broken up more easily during plate reciprocation since the eddy velocity through the free opening area increases. Therefore, in the case of a smaller free opening area, the axial dispersion coefficient is more affected by the reciprocation frequency than by the transverse nonuniformity of the velocity profile due to the maldistribution of droplet size.

Effect of Phase Velocity

The effect of continuous phase velocity (U_c) on E with Arrangements 1 and 3 is shown in Fig. 7. The axial dispersion coefficient with Arrangement 1, which has only perforated plates, increases with an increase in U_c since the eddy velocity through plate holes increases with increasing U_c. The axial dispersion coefficient increases linearly with U_c with perforated plates of free fractional opening areas of 0.087 (*9*) and 0.23 (*13*). On the other hand, Kim and Baird (*8*) reported that the continuous phase velocity does not have a significant effect on E with a perforated plate having a free fractional opening area of 0.57. However, in the present study the rate of increase in E with the continuous phase velocity is less pronounced due to the larger free fractional opening area ($\sigma = 0.6$) than those of Kagan et al. (*9*) and Kasipathi Rao et al. (*13*) since the eddy velocity is less affected by the continuous phase velocity. On the other hand, as can be seen in Fig. 7(b), the axial dispersion coefficient with the fan plate has a maximum value at about $U_c = 2.5$ cm/s. The axial dispersion coefficient decreases with an increase in U_c above 2.5 cm/s since radial mixing increases due to the plate shape.

The effect of the dispersed phase velocity (U_d) on E with Arrangements 1 and 3, which have similar free opening areas, is shown in Fig. 8. As can be seen, the axial dispersion coefficient increases slightly with an increase in U_d. The transverse nonuniformity of the velocity profile increases with increasing U_d since the droplets have more inhomogeneous sizes. However, the transverse nonuniformity decreases with an increase in frequency since the droplets are broken up more effectively with frequency (*8*). Therefore, the rate of increase in E decreases with the reciprocation frequency.

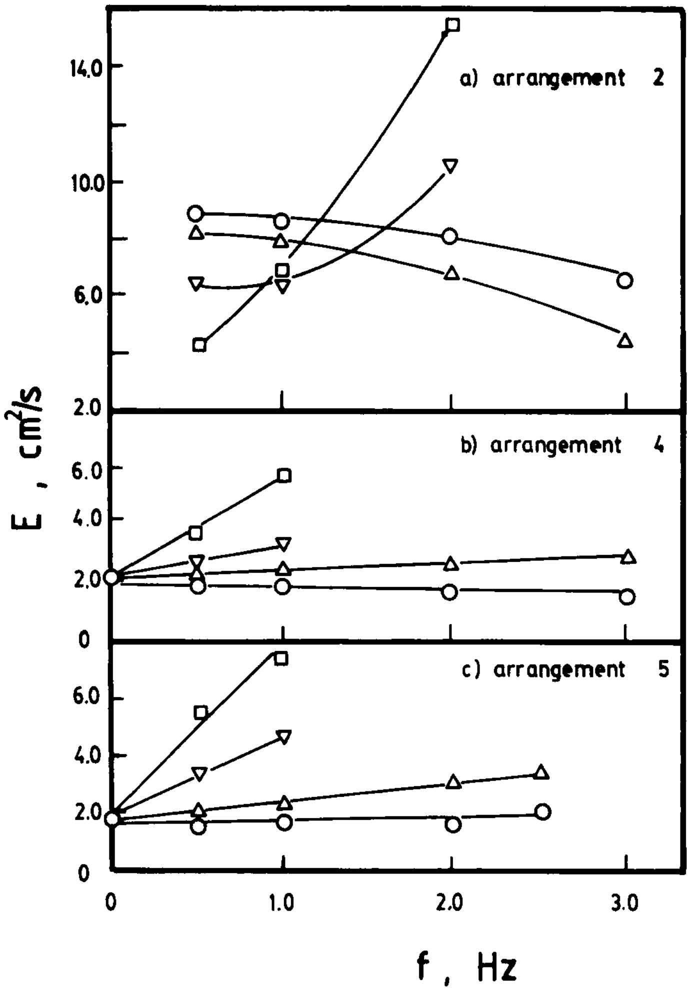

FIG. 6. Effect of frequency on E with various free opening areas of the fan plate at $U_c = U_d =$ 0.25 cm/s. A = (○) 0.635, (△) 1.27, (▽) 2.54, (□) 3.81 cm.

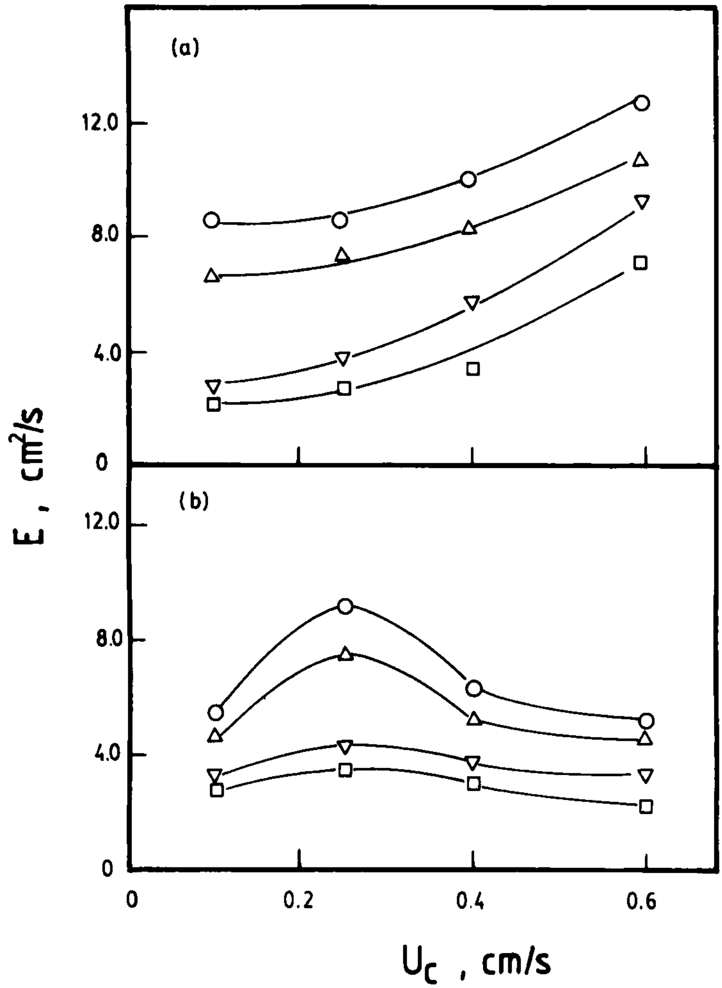

FIG. 7. Effect of continuous phase velocity on E with Arrangements (a) 1 and (b) 3 at U_d = 0.25 cm/s and A = 1.27 cm. f = (○) 0.5, (Δ) 1.0, (∇) 2.0, (□) 3.0 Hz.

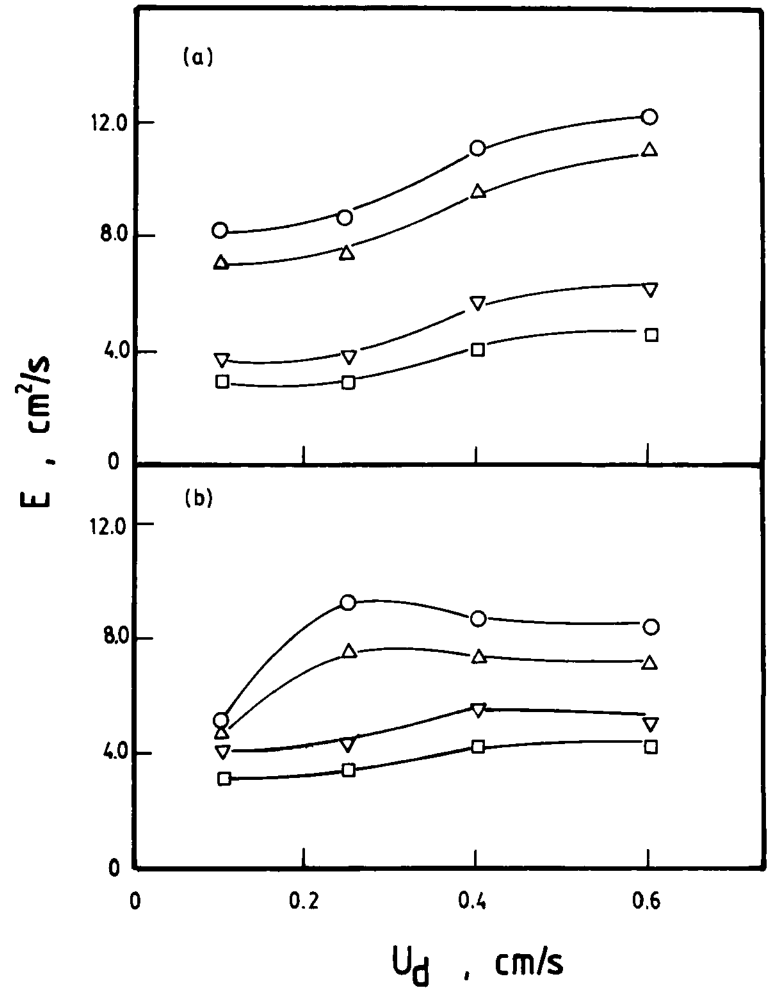

FIG. 8. Effect of dispersed phase velocity on E with Arrangements (a) 1 and (b) 3 at U_d = 0.25 cm/s and A = 1.27 cm. f = (○) 0.5, (△) 1.0, (▽) 2.0, (□) 3.0 Hz.

Dispersed Phase Holdup

In reciprocating or pulsed extraction columns, dispersed phase holdup (ε_d) is a function of agitation intensity and the throughput rate, as observed by previous investigators (*7, 14, 15, 17*). The effect of agitation intensity (*Af*) on ε_d with Arrangements 1, 3, and 6, which have a similar free fractional opening area ($\sigma \simeq 0.6$), is shown in Fig. 9. As can be seen, the dispersed phase holdup increases rapidly with an increase in agitation intensity above 2.5 cm/s since the flow regime is changed from an inhomogeneous dispersed phase flow to the emulsion flow regimes. In Karr columns the plate has a large free opening area, and the mixer settler flow regime cannot be observed (*17, 18*) since the dispersed phase layer under the plate cannot be established. Therefore, the minimum values of ε_d do not exhibit an increase with agitation intensity. As can be seen in Fig. 9, the dispersed phase holdups do not vary significantly with the geometry of plates which have a larger free fractional opening area ($\sigma \simeq 0.6$).

The effect of agitation intensity on ε_d for various free opening areas is shown in Fig. 10. As the free opening area of a plate is reduced, the dispersed phase holdup has larger values and increases more rapidly with an increase in agitation intensity, *Af*. The droplet size decreases with an increasing energy dissipation rate, which increases with a decreasing free opening area (*19, 20*).

The effects of the continuous and dispersed phase velocities on ε_d with Arrangements 1 and 3 are shown in Figs. 11 and 12, respectively. The dispersed phase holdup increases slightly with an increase in U_c. In countercurrent columns, the residence time of the dispersed phase increases with U_c since the drag force on a droplet increases with an increase in U_c. On the other hand, the residence time of the dispersed phase increases further with an increase in U_c with Arrangement 3 than it does with Arrangement 1, which has only perforated plates, since the droplets are well mixed in the radial direction with an increase in U_c because of the inclined blades.

The dispersed phase holdup increases linearly with an increase in U_d (Fig. 12), as observed by previous investigators (*21*). At a lower frequency the rate of droplet coalescence increases with an increase in U_d since the reciprocation of plates may not break the droplets effectively. As the frequency of reciprocation is increased, the rate of increase in ε_d increases due to intensive droplet breakage caused by higher fluid turbulence from the intensive plate reciprocation.

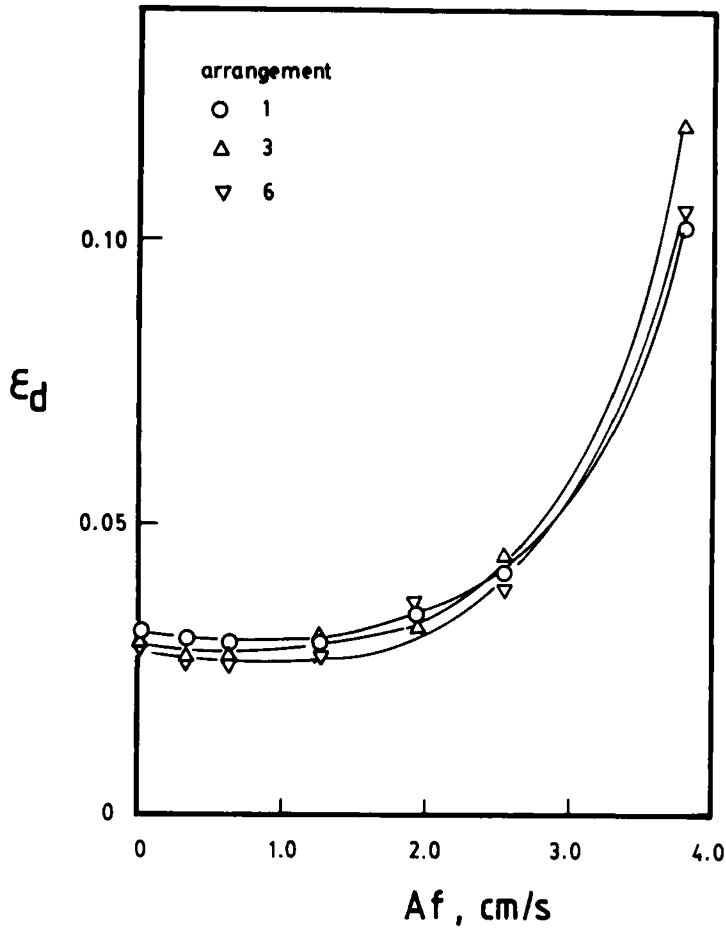

FIG. 9. Effect of agitation intensity and plate geometry on dispersed phase holdup at $U_c = U_d$ = 0.25 cm/s.

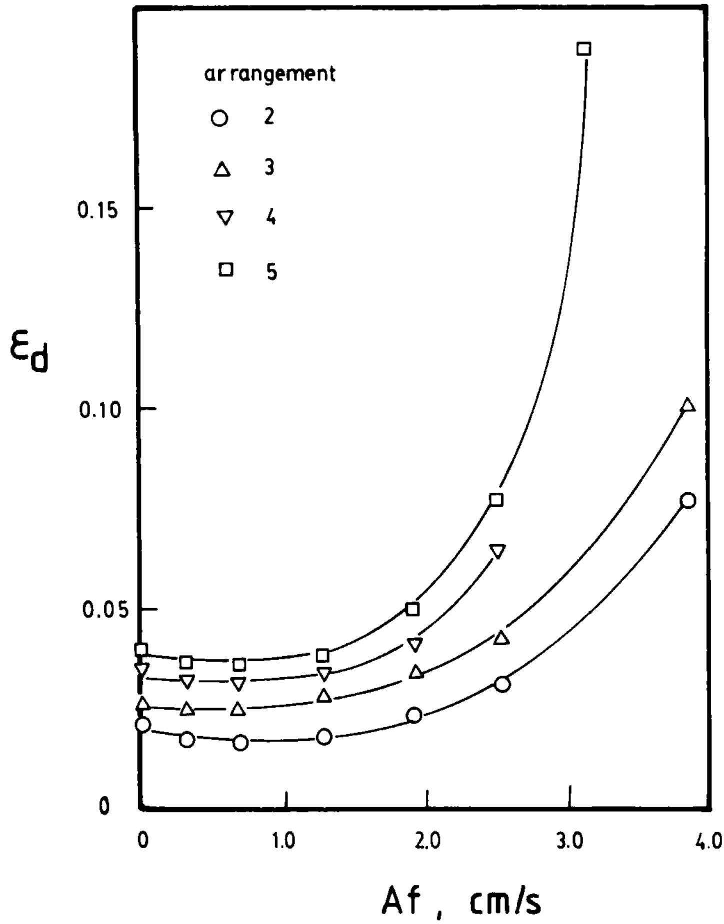

FIG. 10. Effect of agitation intensity on dispersed phase holdup with various free opening areas of fan plates at $U_c = U_d = 0.25$ cm/s.

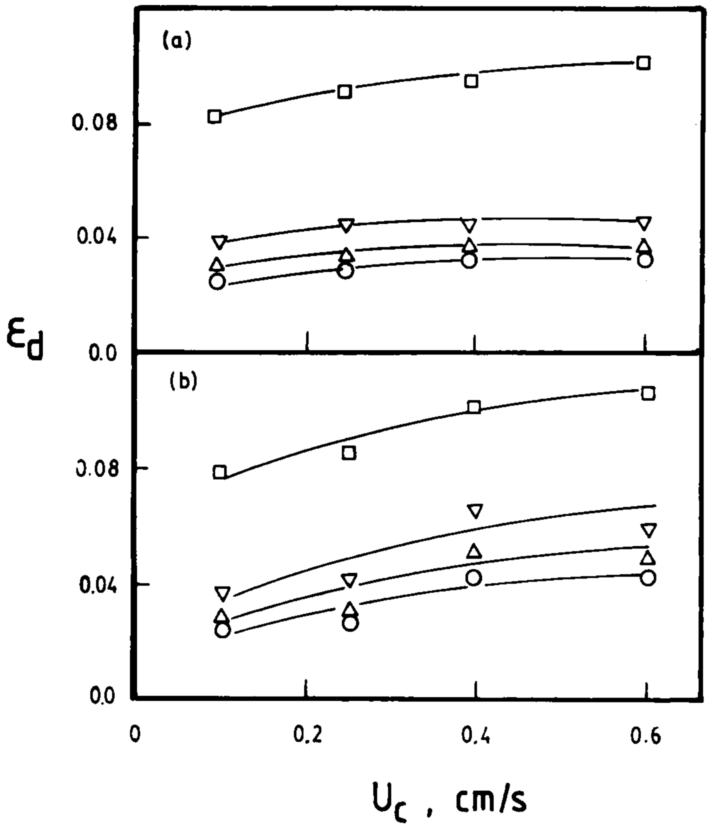

FIG. 11. Effect of continuous phase velocity on dispersed phase holdup with Arrangements (a) 1 and (b) 3 at U_d = 0.25 cm/s and A = 1.27 cm. f = (○) 0.5, (Δ) 1.0, (∇) 2.0, (□) 3.0 Hz.

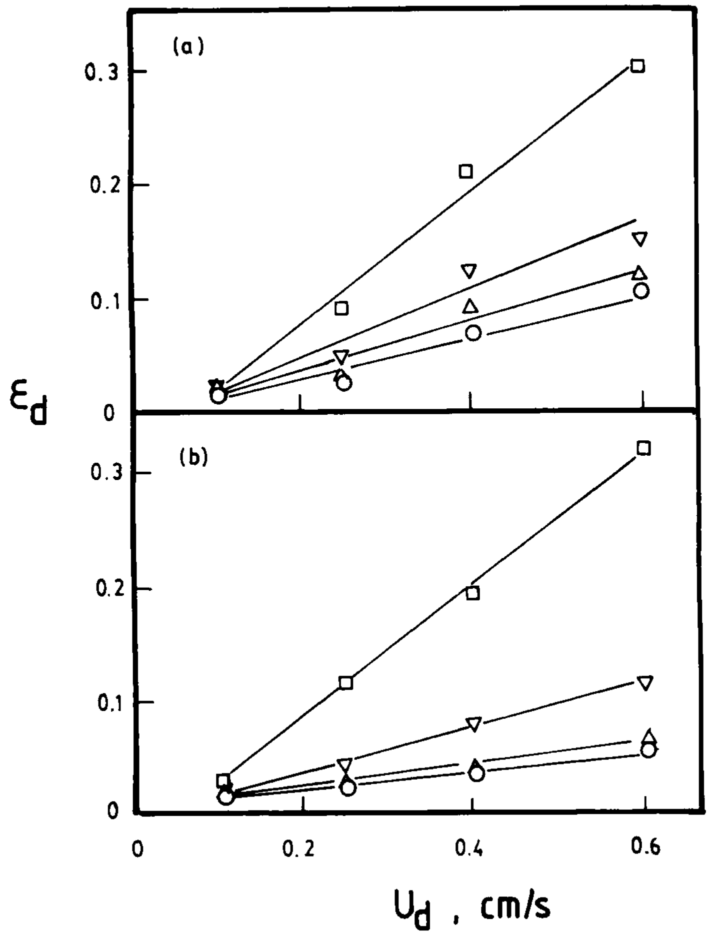

FIG. 12. Effect of dispersed phase velocity on dispersed phase holdup with Arrangements (a) 1 and (b) 3 at U_d = 0.25 cm/s and A = 1.27 cm. f = (O) 0.5, (Δ) 1.0, (∇) 2.0, (□) 3.0 Hz.

CORRELATIONS

Previous investigators (*13, 22*) have reported that E increases linearly with the agitation intensity, Af. However, previous investigators (*2, 7, 10, 13*) have found a relationship between E and A^2f, which has the same dimension as E.

In the present study the fan plate gives a linear relationship between E and A^2f. The axial dispersion coefficient decreases with the amplitude and frequency in the inhomogeneous dispersed phase flow regime ($Af < 2.54$ cm/s) but increases in the emulsion flow regime ($Af \geqslant 2.54$ cm/s). Therefore, the present experimental data on E have been correlated as the following equations. In an inhomogeneous dispersed phase flow regime ($Af < 2.54$ cm/s):

$$E = (15.0 - 1.82A^2f)U_c^{0.01}U_d^{0.16}\sigma^{0.73} \quad (1)$$

In an emulsion flow regime ($Af \geqslant 2.54$ cm/s):

$$E = (10.38 - 1.29A^2f)U_c^{0.46}U_d^{0.20}\sigma^{0.39} \quad (2)$$

with regression coefficients of 0.91, respectively.

In addition, the present experimental data on dispersed phase holdup can be correlated with the experimental variables as

$$\varepsilon_d = 0.13(Af)^{0.67}U_c^{0.22}U_d^{0.93}\sigma^{-0.51} \quad (3)$$

with a regression coefficient of 0.83.

CONCLUSIONS

The axial dispersion coefficient decreases with increasing frequency and amplitude in the inhomogeneous dispersed phase flow regime but it increases in the emulsion flow regime. The axial dispersion coefficient with the perforated plate increases with the continuous and dispersed phase velocities. However, the effect of phase velocities on E is less pronounced with the fan plate. The axial dispersion coefficient has been correlated with A^2f, fluid velocities, and the free fractional opening area of the plates.

The dispersed phase holdup increases with an increase in agitation intensity, Af, and it decreases with the free opening area of the plate.

NOMENCLATURE

A amplitude of plate reciprocation (half stroke) (cm)
E axial dispersion coefficient (cm^2/s)
f frequency of plate reciprocation (Hz)
U_c continuous phase velocity (cm/s)
U_d dispersed phase velocity (cm/s)
σ free fractional opening area (-)
ε_d dispersed phase holdup (-)

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