

AN EXPERIMENTAL STUDY OF ELECTROHYDRODYNAMIC DISPERSION FROM A LIQUID FILM FLOWING DOWN AN INCLINED PLATE INTO A CONTINUOUS LIQUID PHASE

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A water film flowing down an inclined copper plate with flash-boards was dispersed as charged drops into a stagnant dielectric liquid phase under a direct electric field applied vertical to the film surface. The dispersion characteristics were examined experimentally for three kinds of dielectric liquids under various operating conditions.

The holdup fraction of the drops formed depends significantly on applied voltage, inclination angle of the plates and flow rate of the film phase. The electrical dispersion from the film phase and the electrical coalescence between drop and film phases contribute to effective agitation between the liquids adjacent to the interface, and rising and falling motion of the drops provides satisfactory mixing in the bulk of the continuous phase.

Introduction

Considerable attention has been focused on engineering applications of electric fields to liquid dispersion, e.g. spray painting,³⁾ ink jet printing,¹⁾ spraying of fuel oil for combustion,^{4,6,7)} etc. Recently, some investigators^{2,11,15)} attempted to apply electrostatic fields to operations of liquid extraction for improving mass transfer efficiencies. However, their studies were performed mainly on drop formation from electrified single or multiple nozzles. If one of two liquid phases can be dispersed directly as liquid drops from a plane interface between the liquid phases into the other liquid phase, development of a novel liquid extractor can be expected; the electrical drop-formation from the surface of the liquid and the drop-coalescence with the liquid produce adequate agitation of the interface itself, and the agitation will contribute to enhancement of the mass transfer efficiency. Many investigators^{8-10,13,14)} have studied experimentally and theoretically the field-induced instability of a flat fluid-liquid interface under electric fields. However, neither experimental nor theoretical investigations have been made of the liquid dispersion from a liquid-liquid interface.

The present study deals with electrical dispersion from a water film flowing down an inclined plate

electrode into a stagnant dielectric liquid phase as a fundamental study for developing a new electrostatic liquid extractor. The dispersion characteristics are investigated over a wide range of operating conditions with several dielectric liquids as the continuous phase.

1. Experimental

1.1 Experimental apparatus

Figure 1 shows a schematic diagram of the experimental apparatus. The test cell [1] was made of transparent acrylic resin for observation of the flowing liquid film and moving drops by use of a camera and a video-recorder [14]. The cell was 85 mm high, 65 mm wide and 250 mm long. The upper [2] and lower [3] electrodes, copper plates 2 mm thick, 45 mm wide and 150 mm long, were fixed at the top and bottom of the cell and were kept 49 mm apart from each other. The upper plate was connected to a high d.c. voltage generator (Brandenburg 2807R) [8]. The lower plate had five flash-boards, 6 mm high, at intervals of 26 mm. They were fixed on the plate with an inclination angle of 60°, as measured from the downstream-side. (The shape and configuration of the flash-boards are shown schematically in Figs. 1, 2b and 11.) The lower plate was grounded through an electrometer (Takeda Riken TR8651) [9] for measuring the electric current between the electrodes. The test cell was set at various angles of inclination against the horizontal plane.

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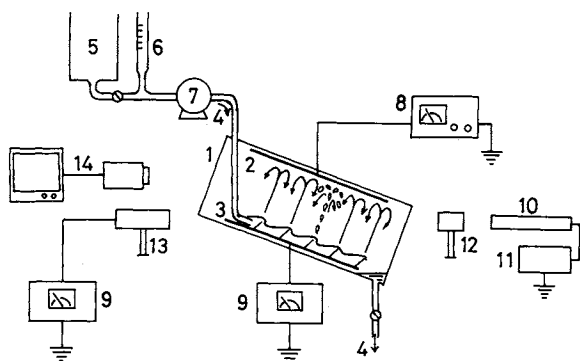


Fig. 1. Schematic diagram of experimental apparatus. 1, cell; 2, upper electrode; 3, lower electrode; 4, path of dispersed phase; 5, dispersed-phase reservoir; 6, flow meter; 7, micro-tube pump; 8, high d.c. voltage generator; 9, electrometer; 10, laser beam source; 11, stabilizer for laser beam source; 12, beam expander; 13, photomultiplier; 14, camera and T.V. system.

1.2 Experimental procedure

The cell was filled with a dielectric liquid as the continuous phase and the liquid was kept stagnant during the experiment. Water was supplied continuously from a reservoir [5] on the lower plate electrode as a film by using a micro-tube pump [7]. The electrical voltage was applied vertical to the interface between the water and dielectric liquid phases. When it approached a certain value (critical voltage, $V_{a,c}$), the water surface began to move with small fluctuations by the field-induced stress. With increasing field strength the fluctuation grew to become waves having conical crest-like shapes of various scales. At an applied voltage higher than the critical one, water drops were violently ejected from the tips of the waves into the continuous phase.

The electrohydrodynamic behavior of the wave formation on the film surface, dispersion from the film phase and motion of the charged drops were visually observed and were recorded by a camera and a T.V. system. The drop size was determined by measuring each diameter of the drop profiles recorded on photographs and the number of drops sampled was 300–500. The drop velocity was determined by the same method as was described in a previous paper.¹²⁾ The number of drops sampled was 50–70.

The holdup fraction of the dispersed phase was obtained from the intensity of laser-beam light transmitted through the continuous liquid phase, including the drops, by using an empirical correlation of the intensity with the drop diameter. The light intensity was measured by an optical system [10–13] and an electrometer [9]. The measurements were carried out

at upper, middle and lower positions in the vertical direction of the cell, and their arithmetic mean was used as the experimental holdup.

The liquids of the continuous and film phases were mutually saturated before each experiment. The physical properties of the liquids used and experimental conditions are listed in Tables 1 and 2, respectively.

1.3 Visual observation of charged drops

Figures 2a and 2b show a frontal view of the wave profile and a side view of the dispersion from the waves, respectively: the film phase flowing down the lower electrode was interrupted by each flash-board; a part of the film phase flowed down over it and the other part was ejected as charged drops from the waves formed on the film surface along the flash-boards into the continuous phase. Moving trajectories of the drops showed roll cell patterns on both upstream and downstream sides of the film-flow, keeping the flash-board as the central axis. The behavior of the drops in the electric field followed this sequence: 1) the drops formed from the waves had induced negative charge and rose against gravity toward the upper electrode (positive polarity) through the continuous phase because of the Coulomb force as the interaction of the drop charge with the electric field; 2) they collided with the upper electrode and their polarity was changed to positive; 3) they fell down through the continuous phase toward the lower electrode by both gravity and the Coulomb force; 4) they coalesced instantaneously with the film phase.

2. Results and Discussion

2.1 Electrical instability of water surface

The fluctuation of the interface between two liquids, which is defined in the present study as the onset of surface instability of the water film, was examined by three kinds of dielectric liquids: *n*-heptane, cyclohexane and a mixed solution of 88 wt% cyclohexane and 12 wt% carbon tetrachloride. The critical voltage for the onset of fluctuation was determined from visual observation. In Fig. 3, the results are plotted against a physical property group with the inclination angle of the plate electrodes as a parameter at constant flow rate of the film phase ($0.8 \times 10^{-6} \text{ m}^2/\text{s}$). At a constant angle of inclination (20°), an experimental correlation between the observed values of $V_{a,c}$ and the physical property group was found for the three kinds of liquids used. For the system of water film in cyclohexane, the value of $V_{a,c}$ decreases with increasing angle of inclination, as shown by the vertical line in the figure. All the observed values of $V_{a,c}$ were far lower than the theoretical ones derived by Lee and Choi⁸⁾ for the case of no flash-board. These results are useful as fundamental information for improving the shape of the flash-board and its arrangement.

Table 1. Physical properties of liquids used at 20°C

Liquid	Density difference [kg/m ³]	Interfacial tension [mN/m]	Viscosity [mPa·s]	Dielectric constant [—]
Water	—	—	1.00	80.1
<i>n</i> -Heptane	312	48.0	0.42	1.91
Cyclohexane	221	46.4	0.95	2.02
Cyclohexane + 12 wt% Carbon Tetrachloride	120	42.9	0.94	2.04

Table 2. Experimental conditions

Applied voltage (positive polarity)	~27	[kV]
Inclination angle of the plates	14–30	[deg.]
Flow rate of the film phase	$(0.6\text{--}2.5) \times 10^{-6}$	[m ² /s]



Fig. 2a. Photograph of frontal view of unstable waves taken from downstream for the system of water film in cyclohexane.

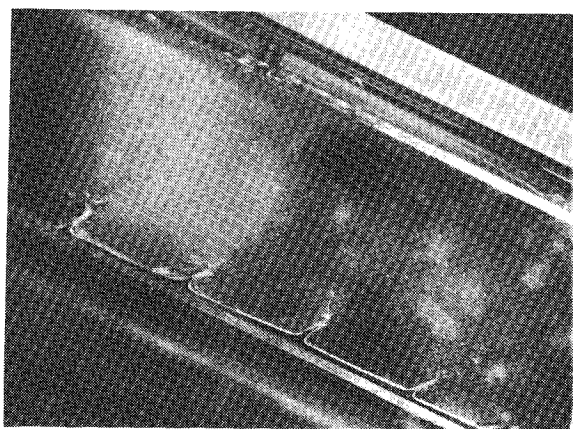


Fig. 2b. Photograph of side view of dispersion from liquid film for the system of water film in cyclohexane.

2.2 Electric current

A relation between experimental electric current per unit area of the electrode and the applied voltage is shown in **Fig. 4** for the system of water film in cyclohexane. The current was proportional to the applied voltage in a range of low voltage; the Ohmic

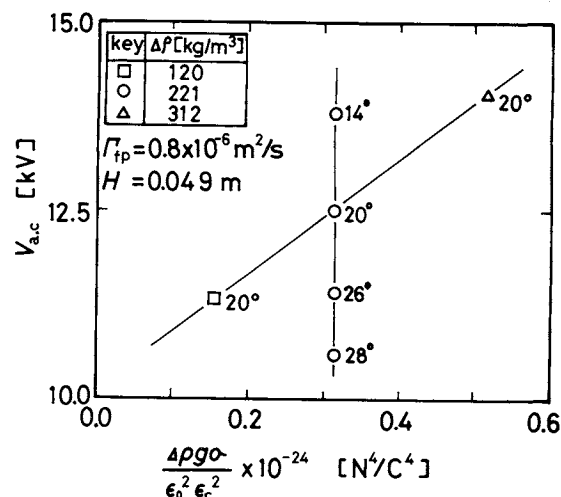


Fig. 3. Relationship between critical applied voltage for onset of instability of liquid interface and physical property group.

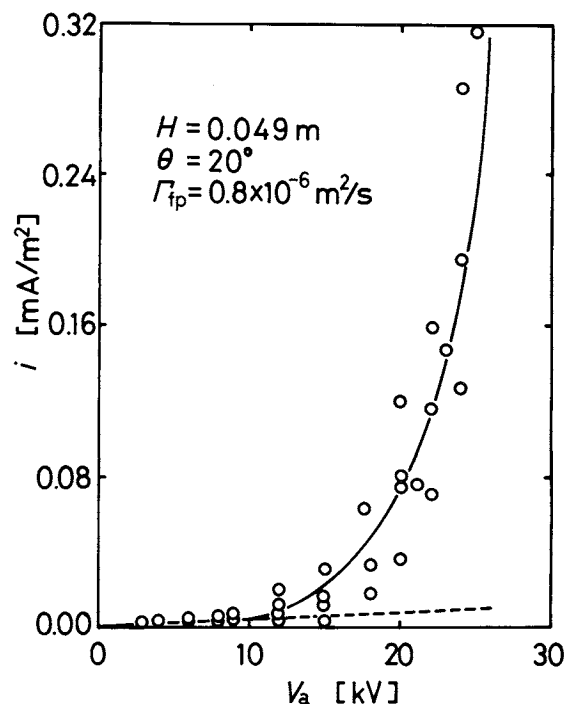


Fig. 4. Relation between electric current per unit area of electrode and applied voltage for the system of water film in cyclohexane.

law was satisfied. The experimental current began to deviate from the Ohmic law at about 12 kV. With increasing voltage above that value, the current increased exponentially. This is due to the increase in number of forming drops which carry electric charges.

2.3 Diameter and moving velocity of charged drops

Plots of Sauter mean diameter of charged drops formed from the waves against the applied voltage are shown in **Fig. 5**. In the cases of cyclohexane and the mixture of cyclohexane and carbon tetrachloride systems, drop diameter increased slightly with increasing applied voltage. Experimental values for the cyclo-

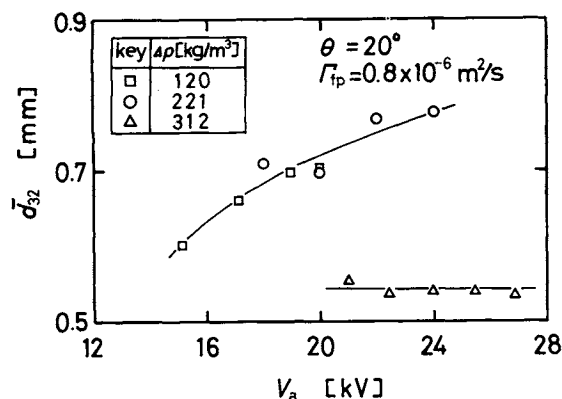


Fig. 5. Sauter mean diameter of charged drops formed from liquid film vs. applied voltage.

hexane system are on the extension of those for the mixed solution system. This is mainly due to the following two reasons: 1) the density difference between cyclohexane and water phases is larger than that between the mixed solution and water phases, and thus the experimental diameters for the former system are shifted toward higher voltage than those for the latter system; 2) both of the organic liquids are similar in viscosity and dielectric constant, and shapes of the waves formed in their liquids are also similar, while water pillars in cyclohexane become longer than those in the mixed solution and the size of the drop produced from the pillar becomes larger in proportion to pillar length. In the *n*-heptane system, on the contrary, drops of constant small size were produced independently of the magnitude of the applied voltage. This is due to the large differences in viscosity and density of *n*-heptane from those of the other two organic liquids. Consequently, the relationship between drop diameter and applied voltage for the system is different from that of the other two systems.

Average velocities of charged drops moving through the continuous liquid phase are plotted against the applied voltages in Fig. 6. A small difference between falling (solid) and rising (open) velocities of the drops is found for each system. This is due to the influence of gravity on the drops. Each of the velocities is significantly high; e.g. the observed falling velocity of a charged drop ($\bar{d}_{32} = 0.7 \text{ mm}$) in cyclohexane was about 155 mm/s, while the terminal velocity of an uncharged drop in the case of the same system and the same drop size was estimated as 13 mm/s by Hu and Kintner's equation.⁵⁾ As mentioned in the previous paper, application of an electric field to drop formation is useful for reducing drop size as well as producing high moving velocity of the drops. Also, higher drop velocity is effective in maintaining internal circulation of the drops.¹⁶⁾ These facts, in addition to the interfacial turbulence (agitation) observed in

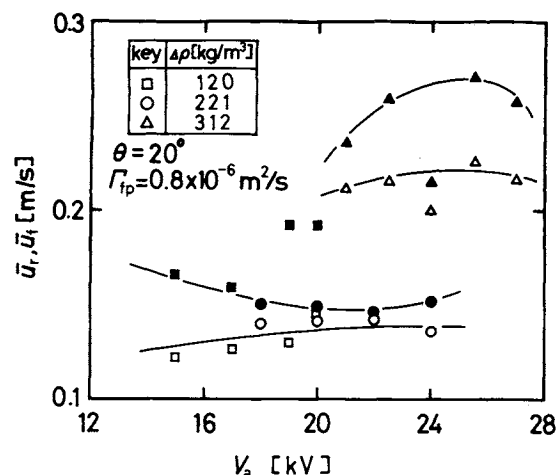


Fig. 6. Moving velocities of charged drops vs. applied voltage.

Open symbol, rising drop; solid symbol, falling drop.

the present experiment, are favorable factors for mass transfer operations in liquid-liquid systems.

2.4 Effects of applied voltage, inclination angle of plate electrodes and flow rate of film phase on holdup fraction of dispersed phase

a) The effect of applied voltage Under a constant inclination angle of the plate electrodes (20°) and a constant flow rate of the film phase ($0.8 \times 10^{-6} \text{ m}^2/\text{s}$), the effect of applied voltage on the holdup fraction was examined. All holdup values obtained for three kinds of liquid-liquid systems are shown in Fig. 7. They increased exponentially with the applied voltage and were correlated with the following dimensionless electric force.

$$\phi \sim \frac{V_a}{V_{a,c}} \approx \frac{V_a}{H \left(\frac{\Delta \rho g \sigma}{\epsilon_0^2 \epsilon_c^2} \right)^{1/4}} \quad (1)$$

The experimental relation between the holdup and the dimensionless electric force is shown in Fig. 8. However, further experiments are needed to obtain an empirical equation.

As the applied voltage was increased, the tips of the waves on the film surface were elongated, maintaining a pillar-like shape, toward the upper electrode and finally the tips contacted that electrode. When this phenomenon occurred, the electrical potential between the two electrodes was short-circuited and dropped to zero value, and the dispersion from the film was interrupted. The short circuit was observed for all the systems, but the minimum value of voltage at which it occurred was different for each system. The electrical short circuit is an unfavorable phenomenon in the operation, but it could be avoided by increasing the distance between the electrodes.

b) The effect of inclination angle of plate electrodes Experimental holdup is plotted against

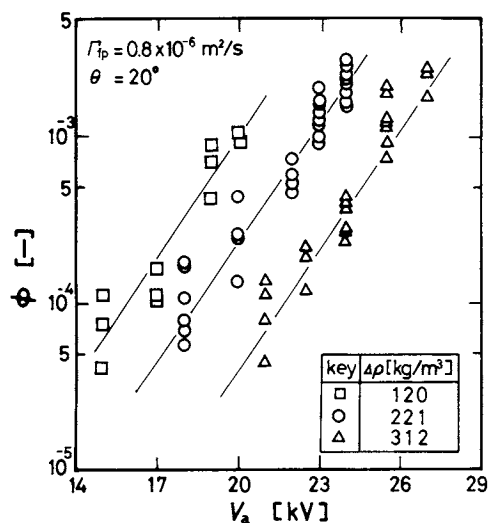


Fig. 7. Relation between holdup fraction of drop phase and applied voltage.

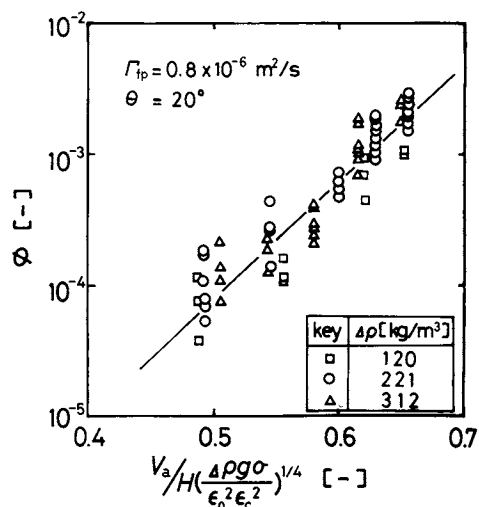


Fig. 8. Relationship between holdup fraction of drop phase and dimensionless electric force.

the inclination angle of the plates in Fig. 9 at a constant applied voltage (20 kV) and a constant flow rate of the film phase ($0.8 \times 10^{-6} \text{ m}^2/\text{s}$) for the cyclohexane system. The holdup increased with the inclination angle of the plates, for the following reason. Although the liquid amount of the film phase collected on the flash-boards decreases with increasing inclination angle of the plate, the film surface is itself deformed into a remarkable convex shape when the film flows just right over the flash-boards. As a result, the electric field strength on the film surface near the flash-boards was enhanced, and the film phase was dispersed more effectively into the continuous phase.

c) The effect of the flow rate of the film phase A plot of holdup fraction vs. flow rate of the film phase is shown in Fig. 10. These results were obtained at a constant applied voltage (20 kV) and a constant inclination angle of the plates (20°) for the cyclo-

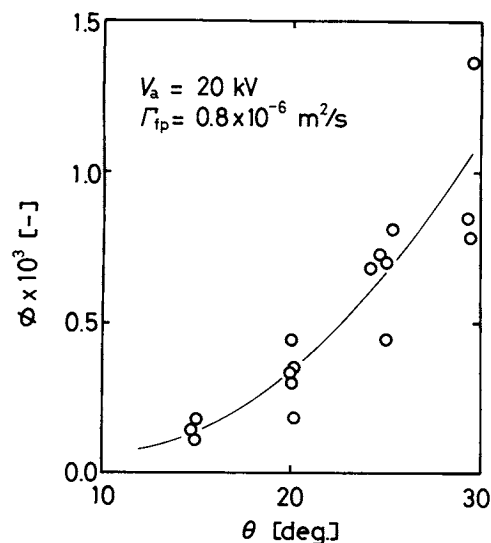


Fig. 9. Dependence of inclination of plate electrodes on holdup fraction of drop phase for the system of water film in cyclohexane.

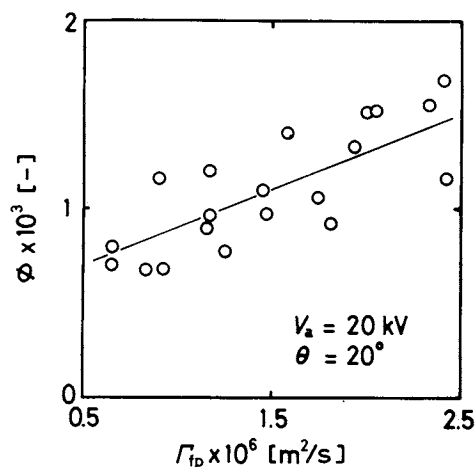


Fig. 10. Dependence of flow rate of film liquid phase on holdup fraction of drop phase for the system of water film in cyclohexane.

hexane system. The holdup fraction increased with the flow rate of the film phase. The reason is similar to that described in Section b).

Although the holdup is not high enough in this experiment, sufficient holdup can be expected by improving the shape of the lower electrode for electrical instability formation at the liquid interface.

2.5 Dispersion rate from film phase

The rate of dispersion from the film phase was calculated as follows. The flow pattern of the dispersion in a compartment between two flash-boards was modeled as shown in Fig. 11. The balance equation for the volumes of rising and falling drops, and the relation between the total holdup fraction of the drops and each holdup fraction of rising and falling drops, are given in Eqs. (2) and (3), respectively.

$$\bar{u}_r \phi_r = \bar{u}_f \phi_f \quad (2)$$

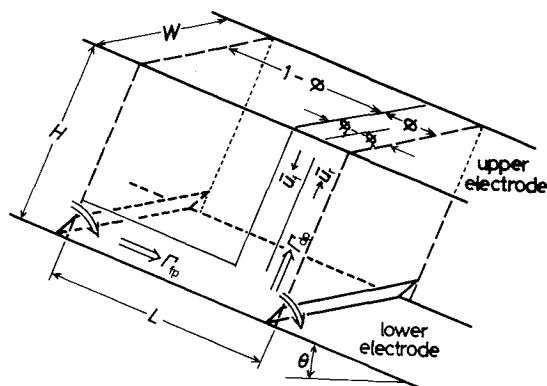


Fig. 11. Schematic diagram of drop phase and film liquid phase flows modeled in a compartment between two flash-boards.

$$\phi_r + \phi_f = \phi \quad (3)$$

From Eqs. (2) and (3), the ϕ_r and ϕ_f are obtained as follows.

$$\phi_r = \frac{\bar{u}_r}{\bar{u}_r + \bar{u}_f} \phi \quad (4)$$

$$\phi_f = \frac{\bar{u}_f}{\bar{u}_r + \bar{u}_f} \phi \quad (5)$$

The flow rate of the dispersion from the film phase is given by Eq. (6).

$$\begin{aligned} \Gamma_{dp} &= \phi_r L W \bar{u}_r / W = \phi_f L W \bar{u}_f / W \\ &= \frac{\bar{u}_r \bar{u}_f}{\bar{u}_r + \bar{u}_f} \phi L \end{aligned} \quad (6)$$

Figure 12 shows an experimental relation between the flow rate of the dispersion and the film flow rate at a constant applied voltage (20 kV) and a constant angle of inclination of the electrodes (20°) for the cyclohexane system. As shown in the figure, the ratio of the flow rate of the dispersed phase to that of the film phase was greater than unity in the present range of film flow rate. This means that the film phase was dispersed into the continuous phase more than once before it flowed over each flash-board. The moving dynamics of the drops in the space between two flash-boards corresponds to the dynamics of more than one stage in a conventional plate column.

A part of the charged drops ejected from the film on a flash-board was carried upstream, fell onto the film in the same compartment between two flash-boards, coalesced with the film phase and was dispersed again. On the other hand, the rest of the drops were carried downstream and coalesced with the film in the next compartment. This means that a part of the liquid film in one compartment was pumped into the next compartment in the form of drops. In the present apparatus, therefore, distributors for liquid dispersion and parting weirs as in

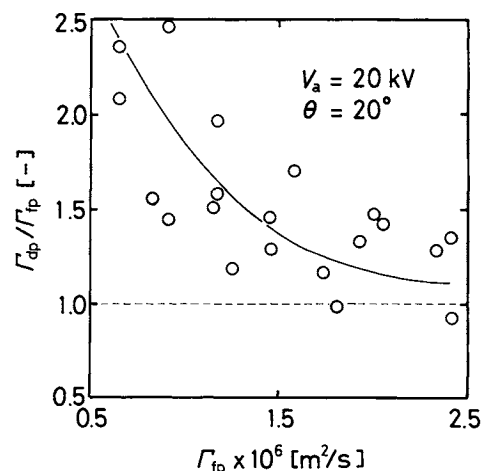


Fig. 12. Ratio of flow rate of drop phase to that of liquid film in a compartment between two flash-boards for the system of water film in cyclohexane.

a conventional plate column are not needed.

Conclusion

Electrical dispersion from waves formed at the interface of water phase into the continuous phase was investigated by applying d.c. voltage for the systems of water film phase in several dielectric liquids under various experimental conditions. Some characteristics of the electrical dispersion found are as follows.

1) Dispersion technique from the liquid film by applying a d.c. electric field can be utilized as a mixing tool for liquid-liquid systems because the dispersion produces marked interfacial turbulence between two-liquid phases as well as bulk mixing in the continuous phase.

2) The behavior of electrical dispersion-coalescence in a compartment between two flash-boards plays a role corresponding to more than one stage in a conventional plate column.

3) Phase separation between the dispersed and continuous phases is superior because charged drops coalesce instantaneously with the film.

4) Holdup fraction of film phase dispersed electrically into the continuous phase increases exponentially with applied voltage, and also increases with the flow rate of the film phase and the inclination angle of the plates. The holdup is correlated with the dimensionless electric force of Eq. (1).

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Nomenclature

\bar{d}_{32}	= Sauter mean diameter of drops from liquid film	[m]
g	= gravitational acceleration	[m/s ²]
H	= distance between electrodes	[m]
i	= electric current between electrodes	[A/m ²]
L	= distance between flash-boards	[m]
\bar{u}	= moving velocity of charged drops	[m/s]
V_a	= applied voltage	[V]
$V_{a,c}$	= critical applied voltage for onset of instability at liquid surface	[V]
W	= width of flash-board	[m]
Γ	= flow rate	[m ² /s]
ϵ_0	= permittivity of vacuum, 8.854×10^{-12}	[F/m]
ϵ_c	= dielectric constant of continuous phase	[—]
θ	= inclination angle of electrodes	[deg.]
$\Delta\rho$	= density difference between two liquid phases	[kg/m ³]
σ	= interfacial tension	[N/m]
ϕ	= holdup fraction of drop phase	[—]
 <Subscripts>		
dp	= drop phase	
fp	= film phase	
f	= falling drop	
r	= rising drop	

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RESILIENCE ANALYSIS OF HEAT-INTEGRATED DOUBLE-COLUMN DISTILLATION SYSTEMS

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Key Words: Resilience Analysis, Distilling Process, Double-Column System, Heat-Integrated System, Decoupling Control, Multivariable Delay Controller

The resilience in both static and dynamic aspects was investigated for three types of heat-integrated double-column distilling processes. First, the static performance of each distilling process was evaluated by the amount of energy consumption and Type A was found to be more energy-efficient than the other two processes. Second, a decoupling control system was designed for each distilling process in which significant delays in state and control variables are involved, and control responses were compared to confirm that Type B is superior to the other two in dynamic performance. Finally, the resilience of the decoupling control system for distilling processes under consideration was studied in view of both steady-state economics and dynamic-state operability by introducing static and dynamic indices of resilience.

Introduction

In recent years, growing interest has been shown in designing energy-saving systems for distilling processes, since distillation is a typical energy-consuming

unit operation. Heat-integrated double-column distilling is one of the promising energy-saving distillation systems. Tyreus and Luyben,¹⁰⁾ Takamatsu *et al.*,⁹⁾ Buckley,¹⁾ and Lenhoff and Morari⁴⁾ are among the earliest researchers who studied the steady-state or dynamic performance of such double-column systems.

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