extent. Consequently, the condensation of both components, particularly of PAN, can be considered to have proceeded at lower actual supersaturations so that the measured composition-temperature relations deviated to the left as shown in Fig. 3b, especially in the higher-temperature regions.

Conclusion

The rates of solid condensation on a cold disk were measured for phthalic anhydride (PAN) and naphthalene to analyze the condensate compositions from PAN–naphthalene mixed vapors as a function of condensation temperature and feed composition. Good agreement was obtained between measured and calculated compositions based on the measured condensation rates.

Nomenclature

C_f	= film mean molar density	[mol/m³]
K	= condensation rate coefficient	[m/h]
$N(T)$	= rate of condensation at T	[mol/(m²h)]
p	= vapor pressure	[Pa]
T	= temperature	[K]
y, z	= compositions of vapor and condensates in mole fraction, respectively	[—]

⟨Subscripts⟩

b	= bulk	
N	= naphthalene	
PAN	= phthalic anhydride	
s	= disk surface	

⟨Superscript⟩

*	= equilibrium

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CONTINUOUS DEMULSIFICATION OF O/W EMULSION BY MEANS OF AN INCLINED ELECTROSTATIC LIQUID–LIQUID CONTACTOR

Fumiya YOSHIDA, Manabu YAMAGUCHI and Takashi KATAYAMA

Department of Chemical Engineering, Osaka University, Toyonaka 560

The use of emulsion liquid membranes is a notable technique for separation. To use liquid membranes for practical processes, effective demulsification techniques must be established. For example, waste water containing oil droplets released from factories and tankers must be purified for environmental protection or reuse of water.

The authors have developed an electrostatic liquid–liquid contactor and have examined its hydrodynamic characteristics.[1,2] In the study, a water film which flowed down an inclined plate with notched flashboards was dispersed into a dielectric liquid phase by means of electric force. It was found that the contactor had favorable characteristics regarding liquid dispersion, mixing of the liquid phases, phase separation, and so on.[1] In addition, empirical equations were proposed for the drop size formed and dispersed-phase holdup, and it was shown that the drop velocity in an ensemble of drops could be estimated by an empirical equation for single charged drop velocity.[2]

In the present work, application of the contactor to the demulsification of an O/W emulsion was attempted. Demulsification performance was studied in terms of the flow rate ratio, which means the frequency of electric dispersion of the film phase into the continuous phase in the contactor while the film phase flows through the contactor.

1. Experimental

The experimental apparatus was essentially the same as used previously[2] except the inlet part of the contactor, where a cock was newly attached for sampling the emulsion phase supplied. Cyclohexane was used for the continuous phase and the dispersed phase (film phase) was O/W emulsion. The oil phase of the emulsion was carbon tetrachloride (CCl_4) and the other phase was water. A lipophilic surfactant (Span 80) was used for emulsification[*] (concentration of Span 80: 0.01 wt%). The emulsion was made by a homogenizer (Nihon Seiki DX-T) at a mixing speed of 10,000 rpm for ten minutes (average diameter of CCl_4 droplets: 1.0 μm). The weight percent of CCl_4 in emulsion phase prepared was 10 wt%, and the emulsion was diluted with water to about tenfold before the experiment. Thus the CCl_4 concentration in the emulsion phase used was less than 1 wt% at the inlet of the apparatus. This low fraction represents the concentration of an emulsion (waste water) following preliminary treatment. In general, further phase separation of the treated emulsion phase is difficult. The CCl_4 concentration in the film phase at inlet and outlet of the apparatus is analyzed by a gas chromatograph (Shimadzu GC-7A, column packing PEG4000 and PEG1500, TCD detector). Physical properties of liquids used are listed in **Table 1**.

2. Results and Discussion

Figure 1 shows the residual fraction of CCl_4 in the film phase drained from the contactor against the applied voltage for three kinds of dispersed-phase flow rate. The residual fraction is defined by Eq. (1).

$$\eta = (C_{out} - C^*)/(C_{in} - C^*)$$
$$\simeq C_{out}/C_{in}$$

(1)

Table 1. Physical properties of liquids used

	Density [kg/m³]	Viscosity [mPa·s]	Interfacial tension [mN/m]
O/W emulsion	999	1.11	29.9
Cyclohexane	777	0.95	

* Span 80 in the CCl_4 phase ensures the stability of fine CCl_4 droplets in the water phase because its H.L.B. value is low. When a hydrophilic surfactant is used for preparing O/W emulsion in the present experiments, the following result is presumed. As the film phase (emulsion) flows down in the continuous phase (cyclohexane), the surfactant in the water phase is adsorbed at the interface between two phases. The surfactant concentration in the water phase depends on the interfacial area between two phases. Consequently, it is thought that the stability of CCl_4 droplets in the water phase is much lower, and the continuous phase is taken into the water phase as droplets (emulsification).

where $C^* \simeq 0$ and $C_{in} \simeq 0.8$ wt% in the present work. For each flow rate, the residual fraction is nearly constant when the applied voltage is less than 20 kV because the film phase flowing down the lower plate with notched flash-boards is not dispersed. Therefore, it is considered that destruction of CCl_4 droplets in the film phase occurs only when the film phase flows down over flash-boards, and is not influenced by the electric field. However, the fraction decreases with increasing applied voltage in the range from 20 kV to 50 kV because the frequency of dispersion-coalescence of the drops becomes larger with applied voltage. That is, the dispersion and coalescence of the drops cause the destruction of CCl_4 droplets in the film and drop phases. When the applied voltage is higher than 55 kV, the dispersion of the drops into the continuous phase becomes more violent and the residual fraction attains a constant value. The fraction is about 0.05, which corresponds to a concentration of 400 ppm. This value is less than the value of saturated solubility of CCl_4 in water for the binary system (800 ppm). In
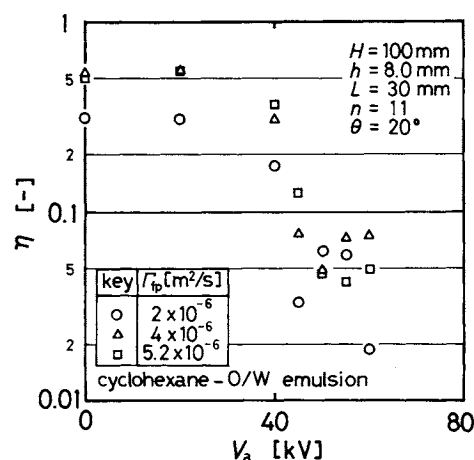

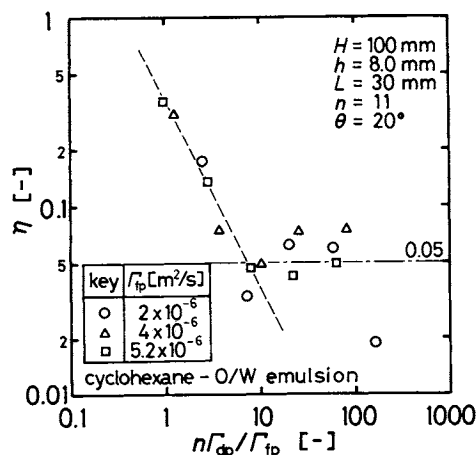**Fig. 1.** Relation between residual fraction of CCl_4 in O/W emulsion and applied voltage

Fig. 2. Relation between residual fraction and flow-rate ratio

the ternary system of cyclohexane, CCl_4 and water, when the CCl_4 concentration as a solute was low, the equilibrium CCl_4 concentration in the water phase could not be detected in the present work, as mentioned above ($C^* \simeq 0$).

The relation between the residual fraction of CCl_4 and the ratio of flow rate of drop phase to that of film phase in the contactor is shown in **Fig. 2**. The flow rate of drop phase (Γ_{dp})[1] is defined as that of drops dispersed from the top of the surface of film phase on each flash-board and is calculated by Eq. (2).

$$\Gamma_{dp} = \bar{u}_r \bar{u}_f \phi L / (\bar{u}_r + \bar{u}_f) \qquad (2)$$

The values of $\bar{u}_r$, $\bar{u}_f$ and ϕ in Eq. (2) are calculated by the empirical equations[2] with operating conditions and physical properties of liquids used. The flow-rate ratio in the figure shows the frequency of dispersion from the film phase while the film phase flows through the contactor. In the region of $n\Gamma_{dp}/\Gamma_{fp} < 10$, the residual fraction decreases with increasing flow-rate ratio, and is inversely proportional to the flow rate of drop phase (broken line in Fig. 2).

$$\eta \propto \Gamma_{dp}^{-1} \sim \phi^{-1} \qquad (3)$$

Equation (3) is valid for the conditions of $n\Gamma_{dp}/\Gamma_{fp} < 10$ and $C_{in} \simeq 0.8\,\text{wt}\%$. According to Eqs. (2) and (3), the flow-rate ratio increases with increasing dispersed-phase holdup, and the greater the flow rate ratio, the better is the demulsification.

When the flow-rate ratio is greater than ten, the residual fraction is nearly constant (dash-dotted line in Fig. 2). As shown in Fig. 2, the demulsification is almost complete when the flow-rate ratio is about ten

and the flow-rate ratio can be increased to more than ten; that is, the flow rate of supplied emulsion (Γ_{fp}) could be increased in the present work. However, the validity of the flow-rate ratio proposed in the present study must be confirmed by accumulating many more experimental data.

Nomenclature

C	= concentration of CCl_4 in O/W emulsion phase	[wt%]
H	= distance between electrodes	[m]
h	= height of flash-board	[m]
L	= distance between flash-boards	[m]
n	= number of flash-boards	[—]
$\bar{u}$	= moving velocity of charged drops	[m/s]
V_a	= applied voltage	[V]
Γ	= flow rate	[m²/s]
η	= residual fraction of CCl_4 in O/W emulsion	[—]
θ	= inclination angle of the plate	[deg.]
ϕ	= holdup fraction of drop phase	[—]

⟨Superscript⟩
*	= equilibrium value	

⟨Subscripts⟩
dp	= drop phase	
f	= falling drop	
fp	= film phase	
in	= inlet	
out	= outlet	
r	= rising drop	

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