EFFECT OF WETTABILITY OF GLASS FIBER BEDS ON SEPARATION OF OIL DROPLETS DISPERSED IN WATER

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Introduction

As one of the conventional methods of separating small oil droplets ($<10\,\mu m$) dispersed in water, the coalescence of oil droplets by fiber beds has been applied widely.[1-7] Although this is an effective method of separation, there are few ways to evaluate the coalescence performance,[1,6] since it might be considered that the extent of coalescence is affected significantly by the wettability by oil of the packing medium used.

In our previous study, we studied the pressure drop across the glass fiber bed and the separation performance of oil droplets by the bed, and presented the correlations to estimate them.[1] In this study, we examined the suitability of the correlations for the fiber beds that were treated by several silane reagents to change their surface wettability by oil.

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1. Experimental

1.1 Experimental procedure

A feature of the separation of oil droplets by fiber bed coalescer is shown schematically in **Fig. 1.** The experimental apparatus used is identical with that of previous work.[1] Three kinds of heavy oil (A, B and C types) were used as oil phase and were dispersed in water at a constant concentration of 1000 ppm. The physical properties of these oils are listed in **Table 1.** The oil-in-water mixtures were fed respectively at constant flow rate to a bed having a cross section of $2.0\times2.0\,cm^2$ from the mixing tank. Oil droplets made contact with each other in the bed and formed larger drops or continuous oil phase. Coalesced oil phases in the bed effused continuously downstream and were captured into the oil reservoir. Sampling was carried out at sampling taps (S_0 and S_L) to obtain the particle concentration of oil droplets upstream and downstream, respectively. Particle concentration was analyzed using a Personal Image Analysis System (LA-500 PIAS Co.). The average of droplet size

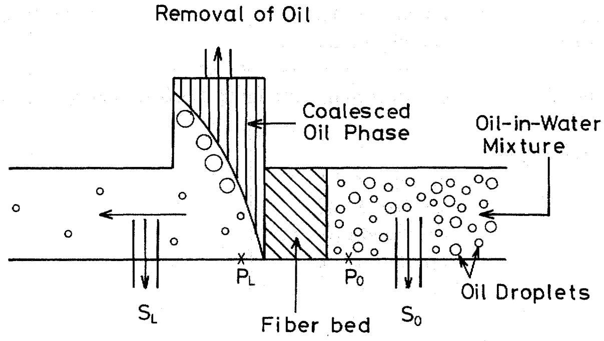

Fig. 1. Schematic features of separation of oil droplets by fiber bed

Table 1. Physical properties of used oil

Type of oil	A	B	C
Density [g/cm^3]	0.85	0.94	0.88
Viscosity [Pa·s]	4.8×10^{-3}	93.3×10^{-3}	117×10^{-3}
Interfacial tension against water [mN/m]	51.8	50.2	53.4

measured upstream for three kinds of oils were 1.5, 1.8 and 2.0 μm, respectively. Pressure drop across the bed was measured as the pressure difference at the points P_0 and P_L by manometer. Oil holdup in the bed was measured by determining the amount of oil accumulated in the bed by the extraction method after an experiment was completed. The length of the bed was varied from 2.0 mm to 7.0 mm and the flow rate was varied from 0.2 cm/s to 0.88 cm/s.

1.2 Fiber bed

Surfaces of glass fibers having diameters of 5.3, 9.0 and 19 μm respectively were coated by two kinds of silane reagents to change their surface wettability by oil. One reagent was octadecyltrichlorosilane ($CH_3(CH_{12})_{17}SiCl_3$), (Aldrich Chemical Ltd.) and another was 1H, 1H, 2H, 2H-perfluorodecyltriethoxysilane ($CF_3(CF_2)_7CH_2CH_2Si(OC_2H_5)_3$, (PCR Co.). The methods of coating these reagents on the surface of glass fibers have been described by Clayfield *et al.*[2] To examine the wettability of these coated glass-fiber surfaces, the critical surface tension (γ_c) was measured. γ_c was obtained from Zisman plots[8] by measuring the contact angle of various organic solvents coated on plane microscope glass slide surfaces in the same way as the glass fibers were coated, and the surface tension of the solvents. The measured values of γ_c were 22 and 17 mN/m for the coating glass fibers (C-1 and C-2) treated by the reagents $CH_3(CH_{12})_{17}$ $SiCl_3$ and $CF_3(CF_2)_7CH_2CH_2Si(OC_2H_5)_3$ respectively, whereas noncoating glass fiber (N-C) gave a γ_c value of 85 mN/m. The bed porosities were 0.935, 0.920 and 0.920 for the fibers of 5.3, 9 and 19 μm diameter, respectively.

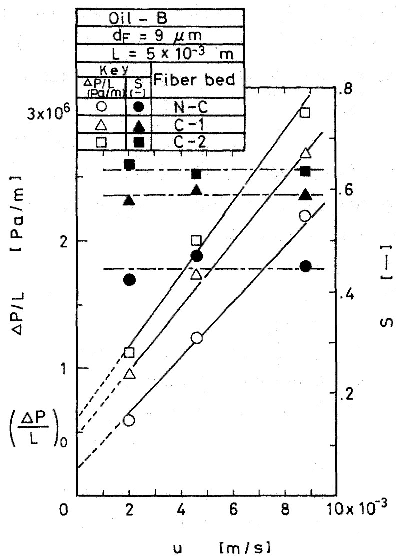

Fig. 2. Relationship between $\Delta P/L$ and S at steady state for three kinds of fiber beds

2. Results and Discussion

2.1 Pressure drop

In our previous study, we presented the following equation to estimate the relationship between pressure drop and fluid velocity at steady state when the oil-in-water mixture passed through the glass fiber bed.[1)]

$$\frac{\Delta P}{L}=\frac{\mu u}{K_s}+\left(\frac{\Delta P}{L}\right)_0 \tag{1}$$

where K_s is the permeability when the mixture passes through the bed and $(\Delta P/L)_0$ is the intercept of the plot of $\Delta P/L$ vs. u. K_s and $(\Delta P/L)_0$ are represented as a function of the oil holdup, S.

$$K_s=\frac{\varphi_s^3}{I_0(1-S)^{3.3}(1-\varphi_s)^2} \tag{2}$$

and

$$\left(\frac{\Delta P}{L}\right)_0=2.3\times 10^{-6} I_0 S^{1.25} \tag{3}$$

Figure 2 shows the relationship between $\Delta P/L$ and S with u at steady state for two kinds of coating glass fiber beds (C-1 and C-2) and non-coating one (N-C). The figure shows that the values of $\Delta P/L$ and S became larger as the value of γ_c decreased. This means that the surface nature of the fiber bed could be regarded as becoming more hydrophobic as the value of γ_c decreases, so that the amount of accumulating oil in the bed increases with decrease in γ_c and it causes an increase in pressure drop across the bed. On the other hand, since $\Delta P/L$ increased linearly and S was constant

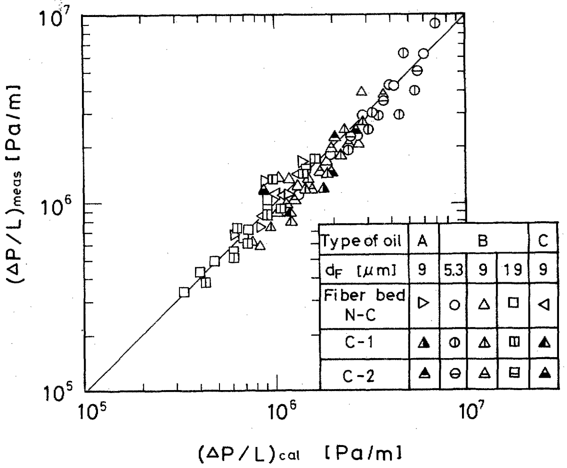

Fig. 3. Comparison of $\Delta P/L$ obtained experimentally at steady state and values calculated by Eqs. (1)–(3)

with increasing u for each bed, it was found that Eq. (1) could be applied to the results of Fig. 2.

Figure 3 shows a comparison of the values of $\Delta P/L$ obtained experimentally for each bed with those calculated by Eqs. (1)–(3). From the figure, it was confirmed that the estimated values of $\Delta P/L$ by Eqs. (1)–(3) agreed well with the experimental results obtained with beds having different surface wettability by oil.

2.2 Separation efficiency of oil droplets

Separation efficiency, Y_f, is defined as follows.

$$Y_f = 1 - \frac{N_L}{N_0} \tag{4}$$

where N_0 represents the numerical fraction of oil droplets upstream and N_L represents that of oil droplets downstream.

Figure 4 shows the effects of fiber diameter, d_F, on Y_f for three kinds of bed (C-1, C-2 and N-C). From the figure, it was found that Y_f decreased rapidly with increasing d_F for N-C bed, but for C-1 and C-2 beds, Y_f showed higher values due to their better wettability by oil, and especially for C-2 bed a Y_f value exceeding $Y_f = 0.7$ was achieved for the separation of even small oil droplets of 1 μm. We studied the effects of several other factors on Y_f and present the following relation, a modification of the equation presented in our previous study,[1] for its estimation.

$$\frac{Y_f d_F^3}{L d_P^2} = 5.0 \times 10^{-7} \left(\frac{\gamma d_F^2}{\mu u d_P^2} \right)^{0.86} (1 - S)^{-0.56} \tag{5}$$

Figure 5 shows the plots of dimensionless groups in Eq. (5) calculated for all experimental data. From the figure, it was found that the experimental data could be correlated by Eq. (5) with a deviation of about ±50% for various fiber beds.

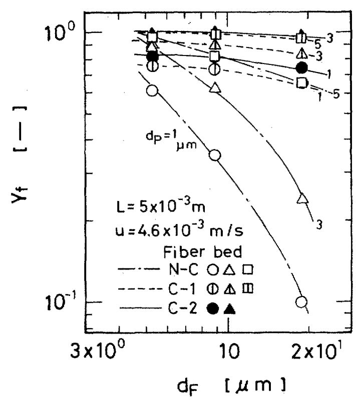

Fig. 4. Effect of d_F on Y_f for three kinds of fiber beds

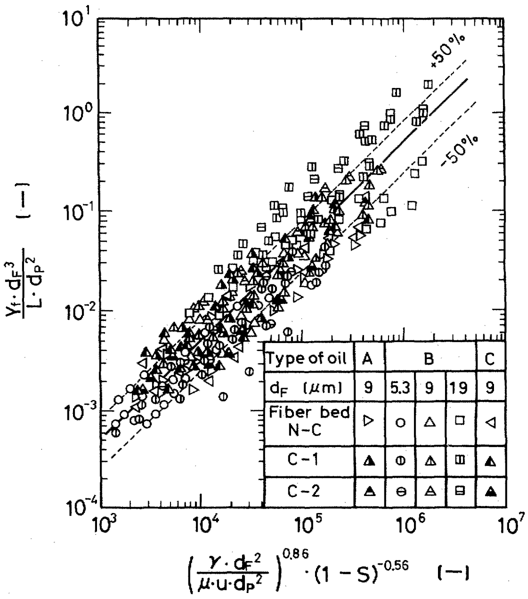

Fig. 5. Correlation of Y_f

Nomenclature

d_F	= fiber diameter	[μm]
d_P	= oil droplet diameter	[μm]
I_0	= parameter defined by $K_0 = \varphi_0 / I_0 (1 - \varphi_0)^2$	[m^{-2}]
K_0	= permeability when water passes through bed	[m^2]
K_s	= permeability when oil-in-water mixture passes through bed	[m^2]
L	= packed-bed length	[m]
N_L	= *numerical* fraction of oil droplets downstream	[—]
N_0	= numerical fraction of oil droplets upstream	[—]
$\Delta P/L$	= pressure drop across the bed	[Pa/m]
$(\Delta P/L)_0$	= defined by Eq. (1)	[Pa/m]
S	= oil holdup in the bed	[—]
u	= liquid velocity	[m/s]
Y_f	= separation efficiency of oil droplets	[—]
γ	= interfacial tension against water	[mN/m]
γ_c	= critical surface tension	[mN/m]
μ	= viscosity of water	[Pa·s]

φ_0 = void fraction when water passes through the bed [—]

φ_s = void fraction when oil-in-water passes through the bed, $\varphi_s = \varphi_0(1-S)$ [—]

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