SEPARATION OF OIL FROM OIL-IN-WATER MIXTURE BY GLASS FIBER BEDS

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Key Words: Coalescence, Oil Droplets, Fiber Bed, Pressure Drop, Oil Hold-up, Correlation Equation

Separation of oil droplets in oil-in-water mixture was studied by using a glass fiber bed coalescer. Fuel oil (B-type) was used as the oil phase and was dispersed in water at a concentration of 1000 ppm. Glass fibers of 5.3 μm and 19 μm diameter were used as packing media. The relationship between the pressure drop across the bed and the oil holdup in the bed at steady state was examined under several experimental conditions and a correlated equation for the relationship was presented. The equation could predict not only the pressure drop at steady state but also those at unsteady states. A new correlation equation for separation efficiency of oil droplets was proposed.

Introduction

A number of methods separating oil droplets from oil-in-water mixture have been presented.[5-15] For droplets larger than 100 μm in diameter, gravity settling, hydrocyclone or centrifuge is usually used to separate them.[5,11,17] For droplets smaller than 10 μm in diameter, membrane filtration techniques can be used.[4] In membrane filtration the membrane has very small pores (less than 1 μm), and usually water and dissolved substances can pass through the membrane while oil droplets are held back. If the membrane has a hydrophobic nature, only oil phase can pass through it.[14] Although good separation efficiency is achieved by this method, the rate of separation of oil is very slow.

In many oily waste water treatments, the separation of oil droplets having diameters from one to several tens of microns is very troublesome. For the separation of oil droplets in this range, gravity settling is ineffective and membrane filtration is economically unattractive because the treatment capacity of oil is small. However, the method of coalescence by packed bed can be used to separate them.[5] In the coalescence method, oil droplets are allowed to come into contact with each other in the bed and form larger droplets or coalesced oil phase which effuses downstream when the oil-in-water mixture passes through the bed. Hence, they can be easily separated by gravity on the downstream side.

Many studies have been made to determine the optimum use of the coalescence method.[1-3,6-10,12,13,16] However, even the manner of evaluating the pressure drop across the bed and the efficiency of oil droplets separation, which are considered to be necessary data for the design of the coalescer, are not yet clear.

In this work the separation of oil droplets in oil-in-water mixture is studied by use of glass fiber beds. A relationship between the pressure drop across the bed and the oil holdup in the bed is examined under various experimental conditions, and an equation which represents the relationship between them is presented. Further, a new correlation for the separation efficiency of oil droplets is discussed.

1. Experimental

A schematic diagram of the experimental apparatus is shown in **Fig. 1**. Flow systems are almost identical to those of previous work,[7] but the size of the apparatus has been changed. Two kinds of commercially available glass fibers, of diameter 5.3 and 19 μm, were used as the packing media. These fibers were packed in the bed at a constant porosity by use of a technique of suction filtration. The porosity of the bed made in this way was 0.935 and 0.920 for the glass fibers of 5.3 and 19 μm, respectively. The bed was attached to a duct having an area of $2.0 \times 2.0\,\mathrm{cm}^2$ with 60-mesh stainless screen. The length of the bed was varied from 0.2 to 0.7 cm. Heavy oil of B-type was used as oil phase and was dispersed in water at a concentration of 1000 ppm for all runs. The oil-in-water mixture in a mixing tank (1) was caused to flow into a bed (3) by a pump (2) at constant flow rate. The flow rate was varied from 0.2 to $0.88\,\mathrm{cm\,s^{-1}}$. In the bed, oil droplets coalesce and the coalesced oil phase effuses continuously downstream and is captured in an oil reservoir (4).

The oil-in-water mixture was sampled from sampl-

Received December 2, 1987. Correspondence concerning this article should be addressed to Y. Akagi.

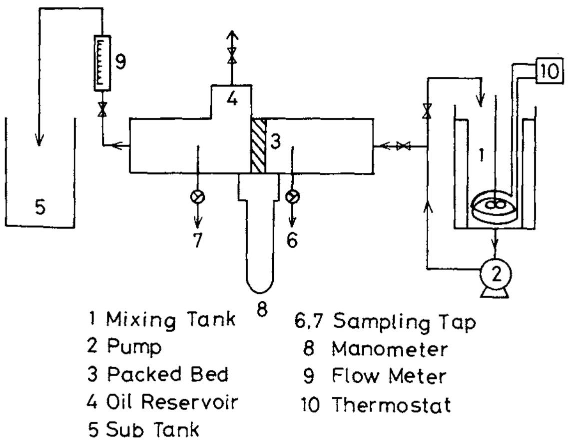

Fig. 1. Flow system of fibrous bed coalescer

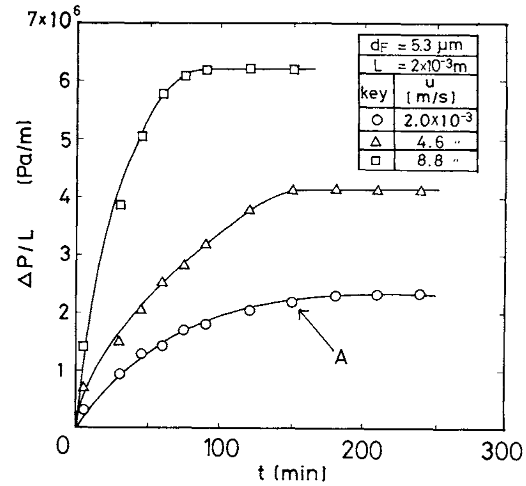

Fig. 2. Variation of $\Delta P/L$ with time at constant flow rate

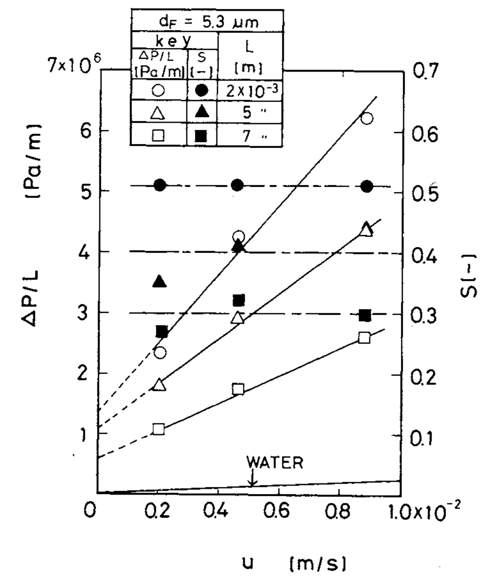

Fig. 3. Relationship between $\Delta P/L$ and S at steady state for 5.3 μm glass fiber bed

ing taps ((6) and (7)) to measure the particle size distribution of oil droplets upstream and downstream, respectively. In this study 30 ml liquid samples were used so as to reduce the experimental errors. The particle size distribution of oil droplets was obtained by using a Personal Image Analysis System (LA-500 PIAS Co.). Pressure drop across the bed and oil holdup in the bed were measured. Data of the oil holdup were obtained from the amount of oil in the bed, which was measured by the extraction method using carbon tetrachloride.

2. Results and Discussion

2.1 Pressure drop and oil holdup

Figure 2 shows the variations of the pressure drop across the bed with time, which was measured at several constant flow rates. The pressure drop, $\Delta P/L$, increases rapidly with time according to three experimental data just after the experiment starts, but becomes almost constant with the lapse of time. In the case of $u=0.2\,\mathrm{cm\,s^{-1}}$, $\Delta P/L$ reaches steady state at about $t=150$ min. After that time, coalesced oil phase begins to appear continuously downstream (see point A in Fig. 2) and is captured by the oil reservoir. When the flow rate increases to $u=0.46$ or $u=0.88\,\mathrm{cm\,s^{-1}}$, the value of the pressure drop at steady state increases and the time to reach steady state decreases. Such changes in $\Delta P/L$ seem to result from the change of the oil volume that accumulates in the bed, i.e., oil holdup in the bed. Therefore, we examined the relationship between the pressure drop and the oil holdup under various experimental conditions.

Figure 3 shows the relationship between the pressure drop and the oil holdup at steady state for a glass fiber bed of $d_F=5.3\,\mu$m, measured at several bed lengths L. In Fig. 3, the empty keys show the data of the pressure drop $\Delta P/L$ and the solid keys show the data of the oil holdup S. Figure 3 also includes the data of $\Delta P/L$ for three bed lengths when only water passed through the bed. In that case, it can be found that the flow obeys Darcy's law because $\Delta P/L$ is linearly proportional to u. On the other hand, when oil-in-water mixture passes through the bed, $\Delta P/L$ varies with bed length. In addition, the values of $\Delta P/L$ and S increase with decreasing L.

Figure 4 shows similar plots to those of Fig. 3 for a glass fiber bed of $d_F=19\,\mu$m. In this case both $\Delta P/L$ and S also increase with decreasing L in the same manner as for $d_F=5.3\,\mu$m.

In general, when single-phase fluid passes through a bed in laminar flow, the relationship between $\Delta P/L$ and u obeys Darcy's law:

$$\frac{\Delta P}{L}=\frac{\mu u}{K_0} \tag{1}$$

and

$$K_0=\frac{\varphi_0^3}{I_0(1-\varphi_0)^2} \tag{2}$$

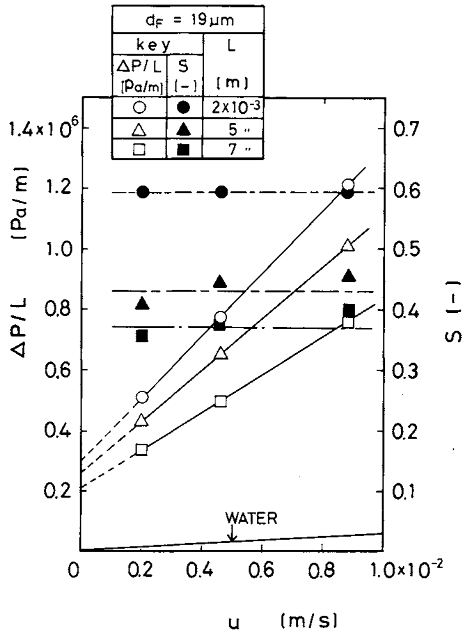

Fig. 4. Relationship between $\Delta P/L$ and S at steady state for 19 μm glass fiber bed

where K_0 is the permeability, φ_0 is the porosity and I_0 is the parameter which represents the packing state of the bed.

Since the data for water can be correlated by Eq. (1) as described above, $I_0 = 1.72 \times 10^{12}$ and $I_0 = 3.16 \times 10^{11}\,\mathrm{m}^{-2}$ are obtained from Figs. 3 and 4 for glass fiber beds of $d_F = 5.3$ and $d_F = 19\,\mu$m, respectively.

For the oil-in-water mixture, we assumed that the relationship between $\Delta P/L$ and u at steady state could be represented as

$$\frac{\Delta P}{L} = \frac{\mu u}{K_s} + \left(\frac{\Delta P}{L}\right)_0 \tag{3}$$

where K_s is the permeability for the oil-in-water mixture and $(\Delta P/L)_0$ means the intercept of the plot of $(\Delta P/L)$ vs. u in Figs. 3 or 4. Both K_s and $(\Delta P/L)_0$ are functions of S. K_s is assumed as follows:

$$K_s = \frac{\varphi_s^3}{I_s(1-\varphi_s)^2} \tag{4}$$

where I_s is the parameter which represents the packing state of the bed and φ_s is the void fraction when the oil-in-water mixture passes through the bed, obtainable by

$$\varphi_s = \varphi_0(1-S) \tag{5}$$

Accordingly, K_s can be estimated by determining I_s as a function of S.

Figure 5 shows the relationship between I_s and S for all experimental data. In Fig. 5, the ordinate is normalized in the form of I_s/I_0. From Fig. 5 it is found that I_s can be represented as

$$I_s = I_0(1-S)^{3.3} \tag{6}$$

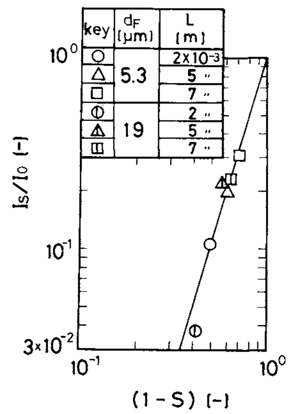

Fig. 5. Plot of I_s/I_0 vs. $1-S$

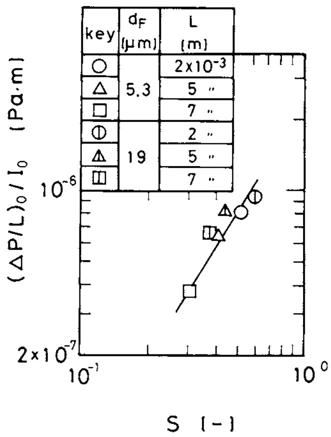

Fig. 6. Plot of $(\Delta P/L)_0/I_0$ vs. S

As described above, $(\Delta P/L)_0$ is also a function of S. From **Fig. 6** it is found that the relation can be represented as

$$\left(\frac{\Delta P}{L}\right)_0 = 2.3 \times 10^{-6} I_0 S^{1.25} \tag{7}$$

With respect to $(\Delta P/L)_0$, Spielman *et al.* have obtained similar experimental results and they have correlated these data with the capillary pressure which acts at the interface between the coalesced oil phase and the water phase in the bed.[12] They reported that the capillary pressure should be included for estimating the total pressure drop because oil–water interfacial forces resist against the interface deformation by the hydrodynamic forces.

From Eqs. (4), (6) and (7), Eq. (3) can be represented as

$$\frac{\Delta P}{L} = \frac{I_0(1-S)^{3.3}(1-\varphi_s)^2 \mu u}{\varphi_s^3} + 2.3 \times 10^{-6} I_0 S^{1.25} \tag{8}$$

Figure 7 shows a comparison of the values of $\Delta P/L$ measured at steady state with those calculated by Eqs. (5) and (8). In Fig. 7, the data for porosities $\varphi_0 = 0.874$ and 0.942 are included. Also Fig. 7 contains the data of Sherony *et al.*[10] and Spielman *et al.*[13] in oil-in-water mixtures. It is found that the experimental data

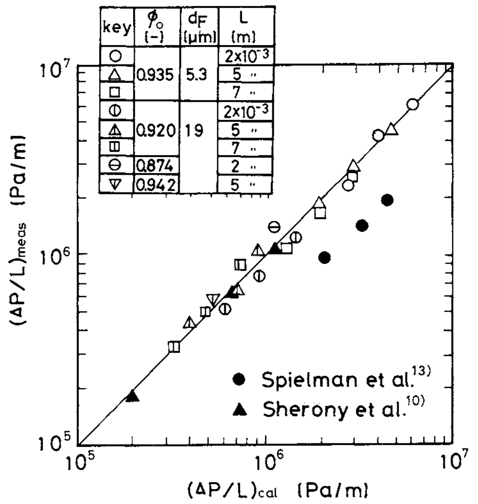

Fig. 7. Comparison of $\Delta P/L$ measured at steady state and values calculated by Eqs. (5) and (8)

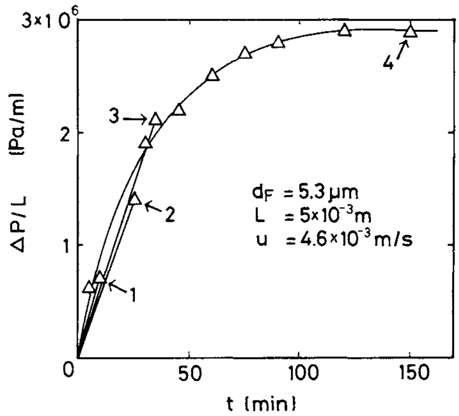

Fig. 8. Experimental data for unsteady state

of Sherony *et al.* agree well with the correlation. An explanation for deviation of Spielman's data from the present correlation may be done by the fact that the different method was applied for measurements of the oil hold up.

From the data at steady state we could find the relation between pressure drop and oil holdup in the bed, and we tried to apply it to the unsteady-state data. Measurement of the pressure drop and the oil holdup in the bed at unsteady state were made. The experimental results are shown in **Fig. 8**. The runs are stopped at points 1, 2 and 3 before the pressure drop reached steady state (point 4), and $\Delta P/L$ and S at the unsteady state were measured. **Figure 9** shows a comparison of the values of $\Delta P/L$ measured at the unsteady state and those calculated by Eqs. (5) and (8). In Fig. 9, points 1, 2, 3 and 4 correspond to respectively to the four points in Fig. 8. Agreement between measured and calculated values is good.

2.2 Separation efficiency of oil droplets

Figure 10 shows an example of particle size distribution of oil droplets upstream. In Fig. 10, N_0 is the frequency distribution curve and R_0 is the cumulative

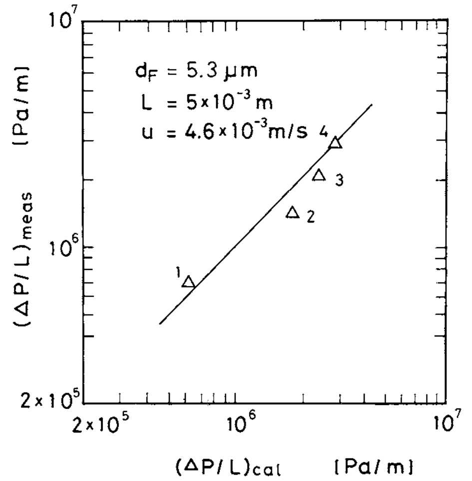

Fig. 9. Comparison of $\Delta P/L$ measured at unsteady state and values calculated by Eqs. (5) and (8)

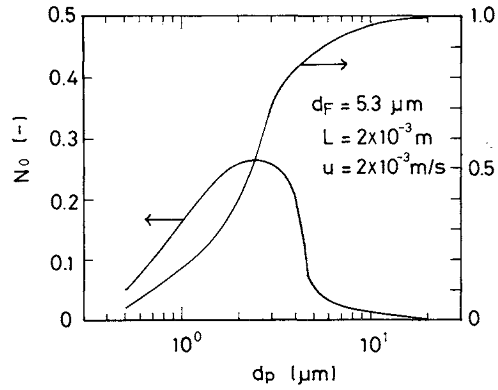

Fig. 10. Particle size distribution of oil droplets upstream

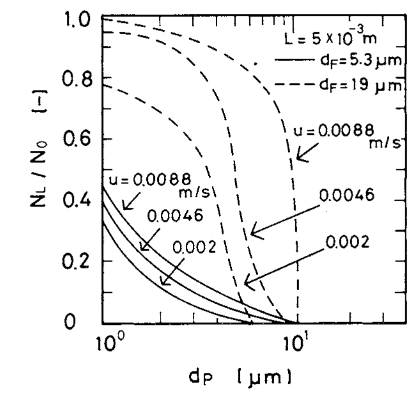

Fig. 11. Effects of d_p and u on N_L/N_0 for glass fiber bed of $L = 5 \times 10^{-3}$ m

distribution curve. Both are shown on the number basis of oil droplets. It is found from these lines that oil droplets upstream were distributed widely, and the median diameter was about 1.8 μm. This upstream particle size distribution curve differed little for all runs carried out in this study.

Figure 11 shows typical experimental data for the state of separation of oil droplets of various diameters at steady state. In this figure, N_L/N_0 shows the ratio of oil droplets frequency downstream to those upstream. It is found from the results at $d_F=5.3\,\mu m$ that N_L/N_0 increases with the increase of u, but that oil droplets above $d_p=10\,\mu m$ are completely separated for all u. Dashed lines in Fig. 11 show the data for $d_F=19\,\mu m$. In that case, N_L/N_0 is larger than that for $d_F=5.3\,\mu m$, hence the separation efficiency is reduced. From these results, the separation efficiency of oil droplets seems to be strongly affected by the flow rate, the fiber diameter and the bed length.

Figure 12 shows the effect of u on the separation efficiency of oil droplets for glass fiber beds of $d_F=5.3$ and $d_F=19\,\mu m$. The separation efficiency, Y_f, is defined as

$$Y_f = 1 - N_L/N_0 \tag{9}$$

From Fig. 12, it is found that Y_f decreases with increasing u for both the beds and its dependence on u varies from u to the -0.3th power to u to the -1.6th power.

Figure 13 shows the effect of L on Y_f. It is found from this figure that Y_f monotonously increases with increasing L and its dependence on L varies from L to the 0.3th power to L to the first power. **Figure 14** shows the effect of d_F on Y_f. It is found from the figure that Y_f rapidly decreases with increasing d_F.

In general, as a parameter to estimate the separation efficiency of solid particles in water through a packed bed, the filter coefficient, λ, is used:

$$\lambda = \frac{-\ln(N_L/N_0)}{L} \tag{10}$$

Spielman *et al.*[13] proposed a correlation for the oil-in-water system by use of λ as follows:

$$\lambda \frac{d_F^3}{d_p^2} = 0.29 \left(\frac{Q d_F^2}{\mu u d_p^4} \right)^{0.25} \tag{11}$$

However, with respect to the filter coefficient defined by Eq. (10), it would be doubtful to use it for predicting the coalescence performance of oil droplets because Eq. (10) involves a simple assumption that the capture of the particles occurs in proportion to the first power of the particles concentration. Therefore, we used Y_f, which can be obtained from only the data of N_0 and N_L, instead of λ. The following correlation equation is proposed as a modified form of Eq. (11):

$$\frac{Y_f d_F^3}{L d_p^2} = K \left(\frac{\gamma d_F^2}{\mu u d_p^2} \right)^b \tag{12}$$

where γ is the interfacial tension.

Figure 15 shows the plot of dimensionless groups in Eq. (12), $Y_f d_F^3/L d_p^2$ and $\gamma d_F^2/\mu u d_p^2$, for all experimental data. The data of Spielman *et al.*[13] are included in this figure. From the solid line drawn through the data, the coefficient $K=6.5\times10^{-7}$ and the exponent $b=0.86$ are obtained. This result means that

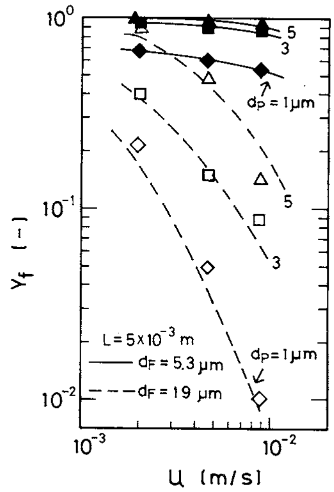

Fig. 12. Effect of u on Y_f for glass fiber beds of $L=5\times10^{-3}$ m

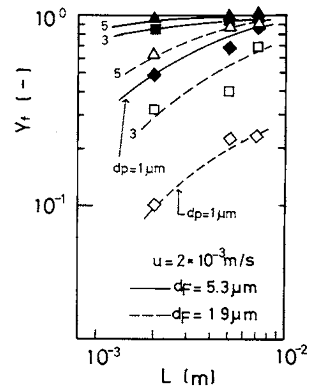

Fig. 13. Effect of L on Y_f for glass fiber beds at $u=2\times10^{-3}\,m\cdot s^{-1}$

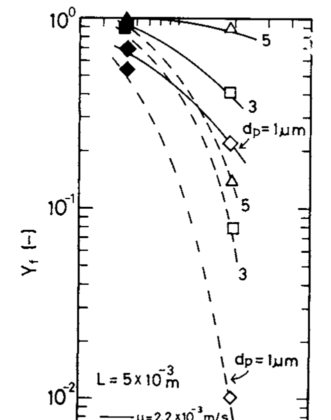

Fig. 14. Effect of d_F on Y_f for glass fiber beds of $L=5\times10^{-3}$ m

$Y_f \propto u^{-0.86} L^1 d_F^{-1.28} d_p^{0.28}$.

The applicable range of Eq. (12) is as follows:

$$2\times10^{-3}\,m\,s^{-1} \leqq u \leqq 8.8\times10^{-3}\,m\,s^{-1},$$

$$2\times10^{-3}\,m \leqq L \leqq 7\times10^{-3}\,m,$$

$$5.3\,\mu m \leqq d_F \leqq 19\,\mu m, \quad 0.874 \leqq \varphi_0 \leqq 0.942.$$

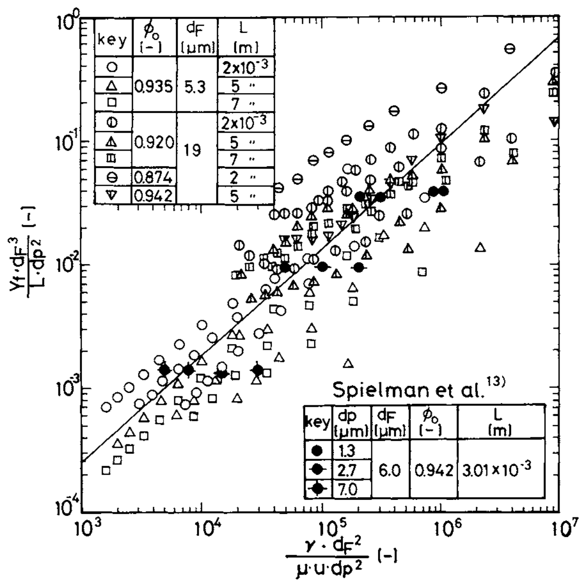

Fig. 15. Correlation of Y_f

Conclusion

In this study the separation of oil droplets in an oil-in-water mixture was examined in glass fiber beds and the following results were obtained.

(1) The pressure drop across the bed and the oil holdup in the bed at steady state were examined under various experimental conditions and an equation which could represent the relationship between them was obtained. It was found that the equation could predict not only the pressure drop for steady state but also those for unsteady state.

(2) The separation efficiency of oil droplets was examined and it was found that the efficiency could be correlated by Eq. (12).

Nomenclature

b	= constant defined by Eq. (12)	[—]
d_F	= fiber diameter	[μm]
d_p	= oil droplet diameter	[μm]
I_0	= parameter defined Eq. (2)	[m^{-2}]
I_S	= parameter defined by Eq. (4)	[m^{-2}]
K	= constant defined by Eq. (12)	[—]
K_0	= permeability of water	[m^2]
K_s	= permeability of oil-in -water mixture	[m^2]
L	= packed bed length	[m]
N_L	= frequency of oil droplets downstream (number base)	[—]
N_0	= frequency of oil droplets upstream (number base)	[—]
$\Delta P/L$	= pressure drop across the bed	[Pa/m]
$(\Delta P/L)_0$	= defined by Eq. (3)	[Pa/m]
Q	= Hamaker constant	[J]
R_0	= cumulative fraction of oil droplets upstream (number base)	[—]
S	= oil holdup in the bed	[—]
u	= liquid velocity	[m/s]
Y_f	= separation efficiency of oil droplet	[—]
γ	= interfacial tension between oil and water	[N/m]
λ	= filter coefficient	[m^{-1}]
μ	= viscosity of water	[Pa·s]
φ_0	= void fraction of water	[—]
φ_s	= void fraction of oil-in-water mixture	[—]

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