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Influence of Oil Properties on Bed Coalescence Efficiency

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ABSTRACT

Bed coalescence efficiency of oil separation from formation water was studied on model systems involving 10 real samples of crude oil and its fractions of different characteristics. Oil components were varied and all other parameters were kept constant, and high mineralization water served as the continuous phase. All experiments were realized on a commercial WO/O4 two-stage bed coalescer. Temperature, oil content, and fluid velocity were kept constant for all samples. Model emulsion was dispersed by constant stirring during the experiment to obtain primarily droplets of 20 μm diameter. Correlations for predicting the coalescence efficiency as a function of some physical and chemical oil properties are presented. The investigated oil components ensured a wide span of viscosity, density, and interfacial tension. The influences of mean molecular weight, neutralization number, as well as the contents of *n*-alkanes, NSO, and aromatics on coalescence efficiency were analyzed. On the basis of the empirical dependences of coalescence efficiency on individual parameters obtained by regression analysis of the data, a general mathematical model was established.

INTRODUCTION

Bed coalescence is a very complex phenomenon involving the effects of a large number of parameters. Hence, for its description it is necessary to combine concepts of two-phase flow through porous media with concepts of water and aerosol filtration to give a theoretical framework for predicting pressure drop, degree of phase separation, and some complicated capillary phenomena occurring in the separation of liquid–liquid dispersions by flow through porous media.

Most studies in the field of bed coalescence have been carried out with the aim of developing models which can be verified experimentally (1–7).

Spielman (1–4) described the fundamental phenomena of two-phase fluid flow through porous media via the capillary pressure, relative permeability, and filter coefficient as a function of local oil saturation and other relevant parameters.

The complexity of the bed coalescence process is the major obstacle to its greater use. The lack of understanding of this process has prevented the formulation of trustworthy general design equations.

Various authors have pointed out different parameters (e.g., viscosity, interfacial tension, wettability, etc.) to be of crucial importance in bed coalescence. Their conclusions were often controversial (6–10), most often because their studies were confined to a relatively narrow range of investigated parameters or they investigated systems with pure organics as the dispersed phase.

In view of the above, we wanted to carry out our study under conditions as close as possible to those in oil field exploitation. For this purpose the experiments were carried out on commercial equipment with real oil samples as the dispersed phase (DP) with a wide range of investigated parameters (density, density difference, viscosity, interfacial tension). In addition, we included the effects of mean molecular weight, neutralization number, content of *n*-alkanes, aromatics, and NSO compounds which, as far as we know, have not been studied before.

EXPERIMENTAL

Equipment and Operating Procedure

All experiments were realized on a commercial coalescer WO/O4, Kikinda Foundry, Yugoslavia (Fig. 1). The coalescer consists of two independent beds formed of two different materials, set in the same coalescer body (11, 12). The emulsion was continuously forced through the filter during 15 hours at a constant flow velocity of 7.2 m/h and a constant temperature of 35°C. The influent oil content in all experiments was 500 mg/L. The oil concentration in the mean samples was measured every 2 hours by IR spectroscopy on a Carl Zeiss Specord 75. Oily water samples were maintained by adding HCl to obtain pH 2. The continuous phase was prepared with a high mineralization of 15 g/L (13.5 g/L NaCl and 1.5 g/L $CaCl_2$). This was necessary to simulate the separation of crude oil

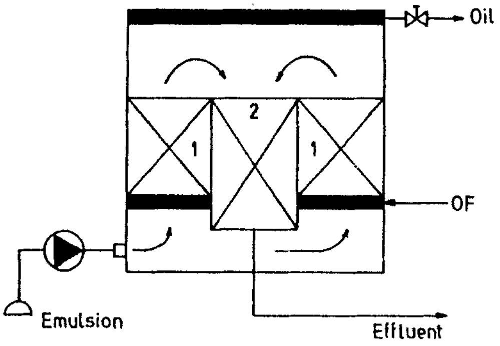

FIG. 1 Schematic diagram of the bed coalescer.

from the formation water. The emulsion was prepared by mixing the components with a stainless steel impeller to obtain oil-in-water droplets with a mean diameter of about 20 μm.

Properties of Filter Media

Waste polymer materials, expanded polystyrene granules (EPS) and polyurethane foam (PU), were used as filter beds in the first and second stages, respectively. Some important physical properties of the filter media are given in Table 1.

Properties of Oil Phase

Seven samples of crude oil from different fields, identified as A–G, and three oil fraction (I–III) serving to cover the range of oil compositions were used as the internal phase. Some physical and chemical characteristics of the oil components are given in Tables 2 and 3.

TABLE 1
Physical Properties of Filter Media

Filter media	Density (kg/m^3)	Bulk density (kg/m^3)	Equivalent diameter (mm)	Uniform coefficient (*l*)	Bed porosity (%)
EPS	37	21	1.34	1.74	0.43
PU	1200	50	—	—	0.96

TABLE 2
Physical Characteristics of Oil Samples

Samples	Density (kg/m^3)	Viscosity (mPa·s)	Mean molecular weight (kg/mol)	Neutralization number (mg KOH/L)	Pour point (°C)
A	912.80	56.31	374	0.979	−30
B	847.15	9.22	217	0.554	15
C	867.44	30.00	251	0.455	29
D	898.20	180.00	460	1.608	33
E	836.04	7.79	201	0.384	12
F	921.68	1132	500	1.466	29
G	866.74	17.48	250	0.491	24
I	973.58	23.28	236	0.396	−30
II	861.80	11.64	271	0.102	−30
III	844.73	21.73	349	0.229	−30
Interval	836–974	7.00–1132	200–500	0.100–1.600	−30–33

TABLE 3
Chemical Characteristics of Oil Samples

Samples	*n*-Alkanes (% w/w)	Aromatics (% w/w)	NSO (% w/w)	Vapor compounds (% w/w)	Asphaltenes (% w/w)
A	22.84	25.14	13.25	0.10	1.40
B	32.69	9.78	14.25	21.62	0.49
C	34.47	23.12	10.72	2.23	0.45
D	20.24	21.01	9.71	2.35	0.42
E	36.66	14.53	5.69	19.92	1.28
F	7.64	19.42	34.23	5.91	0.07
G	34.46	16.36	7.92	10.36	1.68
I	—	42.50	5.09	1.12	0.22
II	—	5.01	0.00	0.00	0.00
III	—	3.13	0.85	0.00	0.00
Interval	7–37	3–43	0–35	0–22	0–1.40

TABLE 4
Some Characteristics of Emulsion

Samples	Zeta potential (mV)	Interfacial tension (mN/m)
DMA	−125	18.80
DMB	−87	20.40
DMC	−76	14.80
DMD	−74	12.19
DME	−92	17.03
DMF	−38	11.56
DMG	−83	14.57
DMI	−43	13.69
DMII	−40	21.32
DMIII	−79	18.04

Characteristics of Emulsion

The investigated emulsions were characterized by measuring the zeta potential of oil droplets on a Rank Brothers Microelectrophoresis apparatus MKII and the interfacial tension on a spinning drop interfacial tensiometer, Model 500, Corexport. The results obtained are given in Table 4. The acronyms (DMA, etc.) represent different dispersion models (DM) containing different oil components (A, B, . . .).

Coalescence Efficiency

The coalescence efficiency was calculated on the basis of the oil contents in the influent and effluent by using the expression

$$E\,(\%) = \frac{C_0 - C_e}{C_0}\,100 \tag{1}$$

where C_0 is the oil content in mg/L in the influent (500 mg/L) and C_e is the oil content in the effluent (mg/L).

As each experiment lasted 15 hours and the oil content in the composite samples was measured every 2 hours, we obtained both the time dependence of the effluent oil content and the coalescence efficiency.

RESULTS AND DISCUSSION

It should be pointed out that in the experimental setup used, a number of separation mechanisms are also involved apart from bed coalescence.

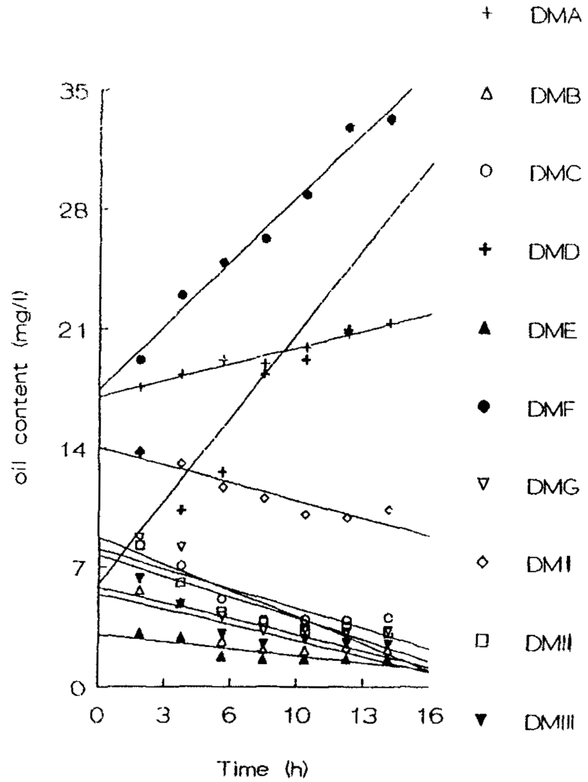

FIG. 2 Time dependence of oil content in the effluent.

These mechanisms are inertia, coalescence at the liquid–liquid interface on the oil film in front of the first bed (Fig. 1), coalescence at two different solid surfaces, and gravity settling. All these mechanisms, acting simultaneously, ensure a low oil content in the effluent (Fig. 2) and a high separation efficiency (Fig. 3).

Statistics of the experimental data are presented in Tables 5 and 6.

As can be seen from Figs. 2 and 3, we can generally distinguish two groups of samples. Samples of the first group (DMB, DMC, DME, DMG, DMI, DMII, and DMIII) are characterized by a low mean oil content in the effluent (less than 5 mg/L), with the trend of a linear decrease with

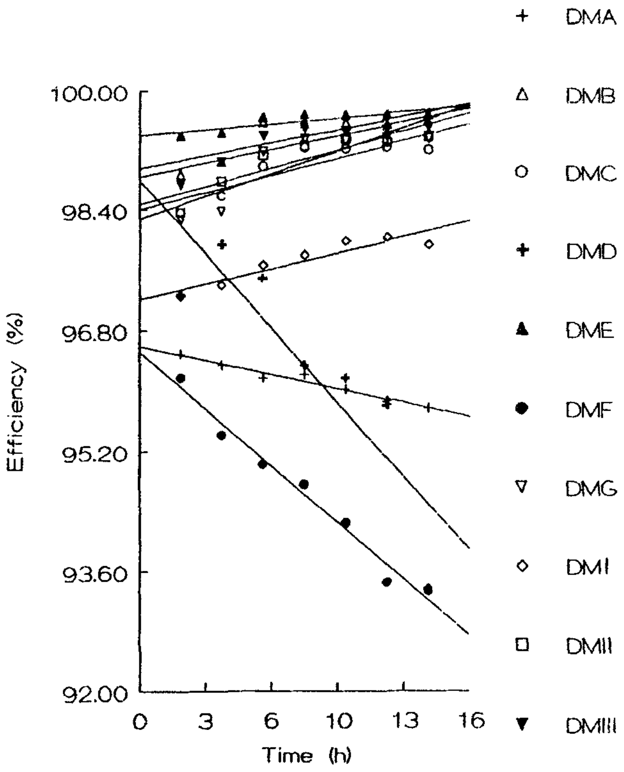

FIG. 3 Time dependence of coalescence efficiency.

TABLE 5
Statistics of Oil Content in the Effluent (mg/L)

Samples	Maximum	Minimum	Mean	Standard deviation	R_{val}
DMA	21.3	17.6	19.4	1.32	0.980
DMB	5.6	2.1	3.1	1.46	0.836
DMC	8.2	3.8	5.1	1.81	0.871
DMD	33.2	10.3	18.3	7.61	0.875
DME	3.01	1.6	2.0	0.65	0.825
DMF	33.3	19.2	26.9	5.16	0.989
DMG	8.7	3.1	4.8	2.47	0.847
DMI	13.8	9.9	11.4	1.53	0.926
DMII	8.2	3.1	4.6	1.90	0.879
DMIII	6.3	2.4	3.5	1.49	0.841

TABLE 6
Statistics of Separation Efficiency Data

Samples	Maximum	Minimum	Mean	Standard deviation	R_{val}
DMA	96.5	95.8	96.1	0.26	0.980
DMB	99.6	98.9	99.4	0.30	0.788
DMC	99.2	98.4	99.0	0.36	0.871
DMD	97.9	93.4	96.3	1.52	0.875
DME	99.7	99.4	99.6	0.13	0.825
DMF	96.2	93.3	94.6	1.03	0.989
DMG	99.4	98.3	99.0	0.49	0.847
DMI	98.0	97.2	97.7	0.30	0.926
DMII	99.4	98.4	99.1	0.38	0.879
DMII	99.5	98.7	99.3	0.30	0.841

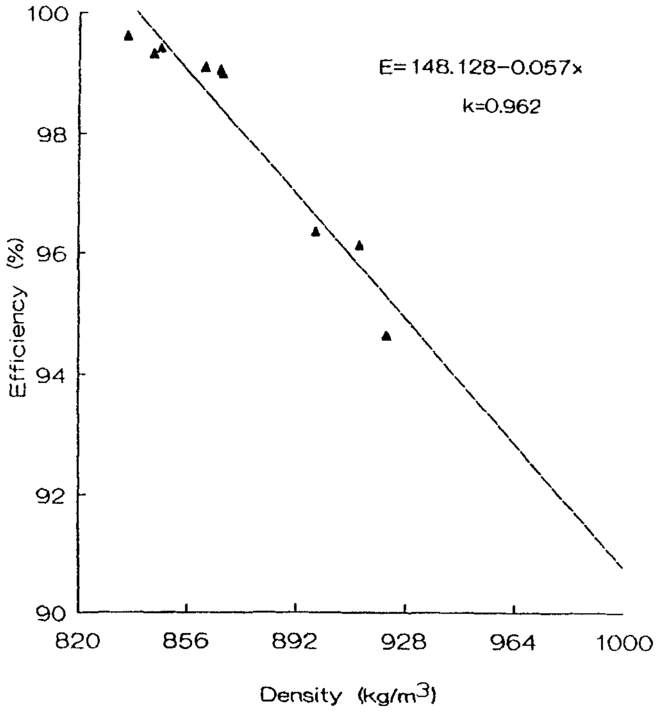

FIG. 4 Dependence of coalescence efficiency on the density of DP.

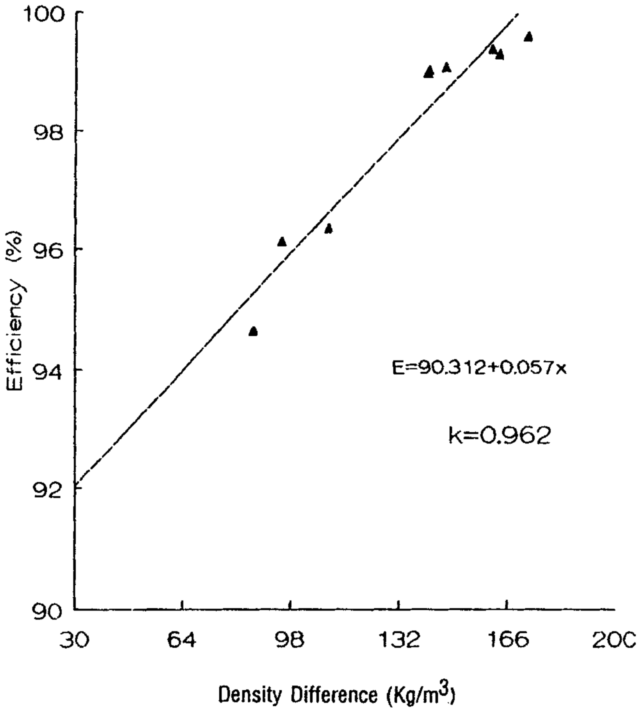

FIG. 5 Dependence of coalescence efficiency on the density difference of DP.

time. The second group of samples (DMA, DMD, and DMF) have a higher oil content (more than 18 mg/L) and show a linear increase with time.

The dependencies of the mean coalescence efficiency on particular parameters of the oil phase, together with the corresponding empirical equations, are presented in Figs. 4–12.

Figures 4 and 5 show the dependence of coalescence efficiency on the density of DP and density difference, respectively. As can be seen, a linear increase with high correlation coefficients (0.962 for both) were obtained in a wide range of the parameters. Jeffreys and Davies (10) state that the rest time usually increases with an increase in density difference

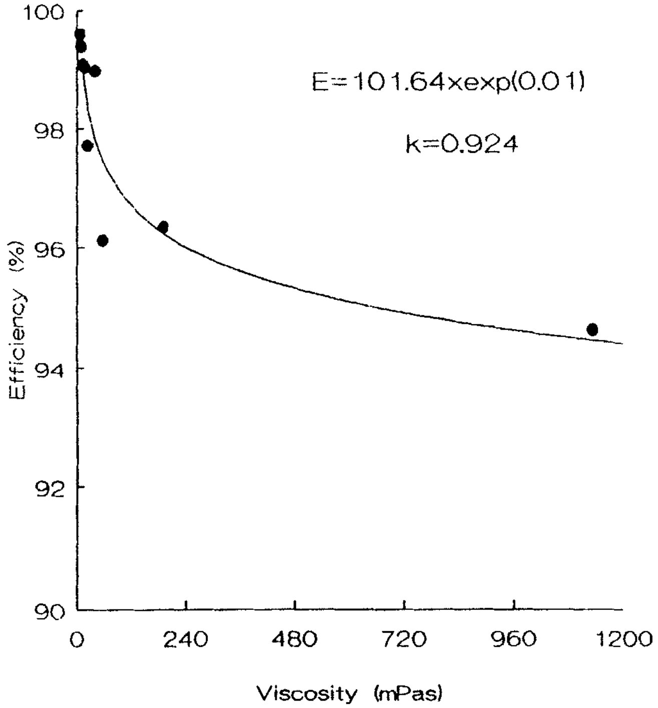

FIG. 6 Dependence of coalescence efficiency on the viscosity of DP.

between the phases, which implies a decrease in the coalescence efficiency. In our case, the observed increasing trend may be explained by a pronounced gravity settling due to two effects—a large density difference and an increased size of droplets coalesced on the surface of two solid filter media.

The dependence of DP viscosity as presented in Fig. 6 is quite similar to that given by Sareen et al. (9). However, some opposing findings can also be found in the literature (8, 10).

Jeffreys and Davies (10) state that these two opposite effects depend on the interfacial tension. A high interfacial tension results in a drop resisting

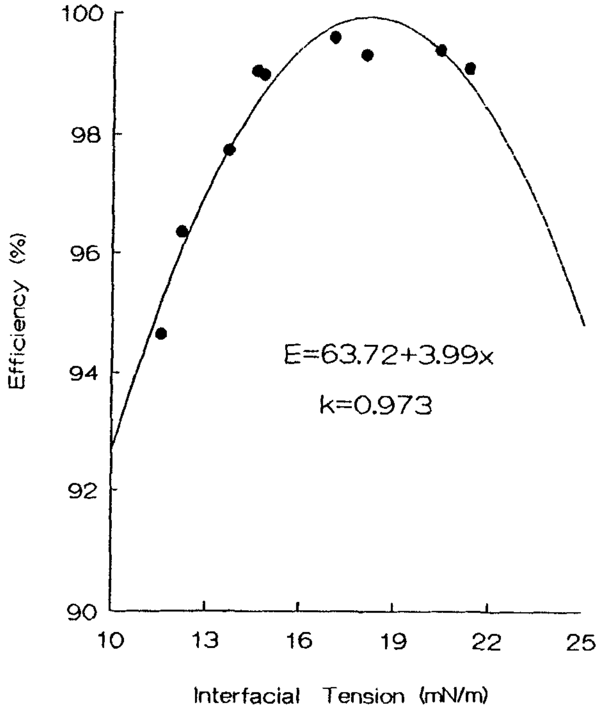

FIG. 7 Dependence of coalescence efficiency on the interfacial thesion of DP.

deformation, so the area of the drainage film will tend to decrease as the interfacial tension increases. Thus, coalescence time tends to decrease with an increase in interfacial tension. However, an increase in interfacial tension also tends to inhibit flow of the film itself, so here again the physical property produces two opposing effects. Generally, however, coalescence time decreases with an increase in interfacial tension. Our results (Fig. 7) confirm the existence of two opposite effects: there are both increasing and decreasing dependence between the coalescence efficiency and interfacial tension. It should be emphasized that this observation was made possible by the wide span of interfacial tension obtained using real oil samples and not by adding surfactants (5, 6).

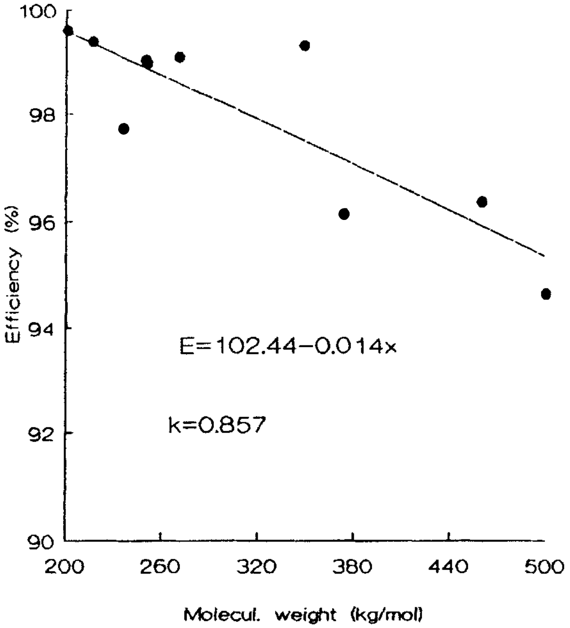

FIG. 8 Dependence of coalescence efficiency on the mean molecular weight of DP.

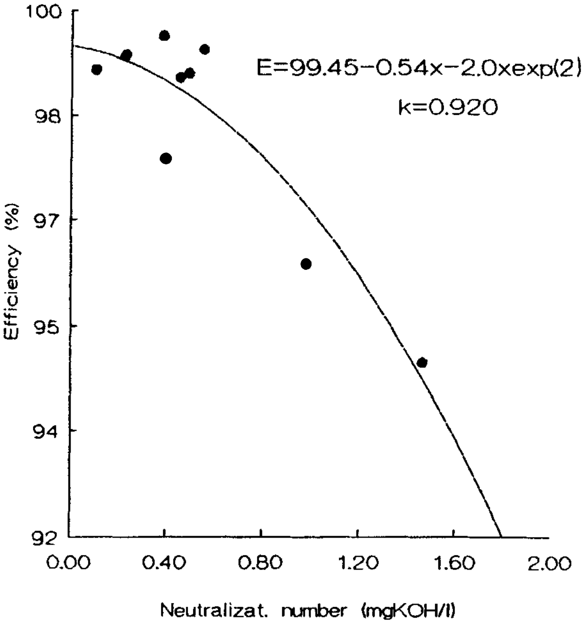

FIG. 9 Dependence of coalescence efficiency on the neutralization number of DP.

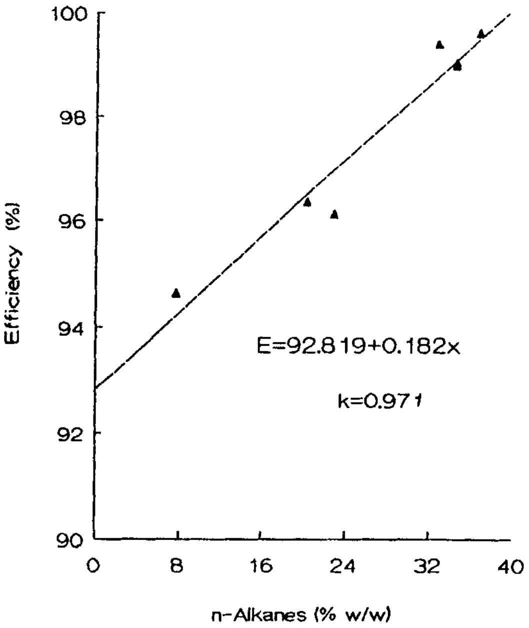

FIG. 10 Dependence of coalescence efficiency on the *n*-alkanes content in DP.

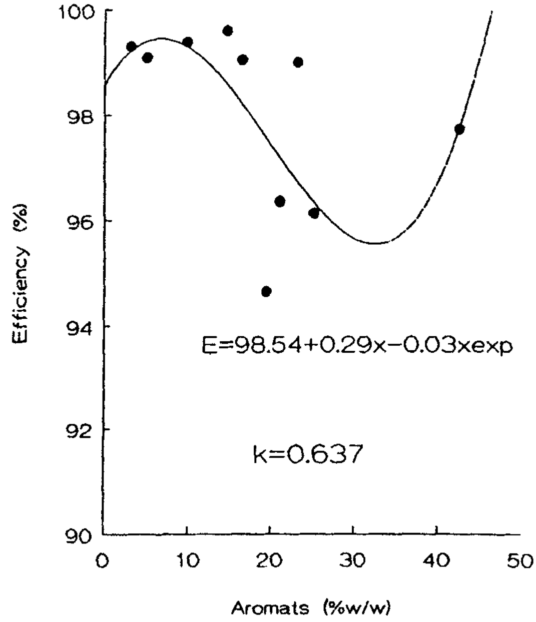

FIG. 11 Dependence of coalescence efficiency on the aromatics content in DP.

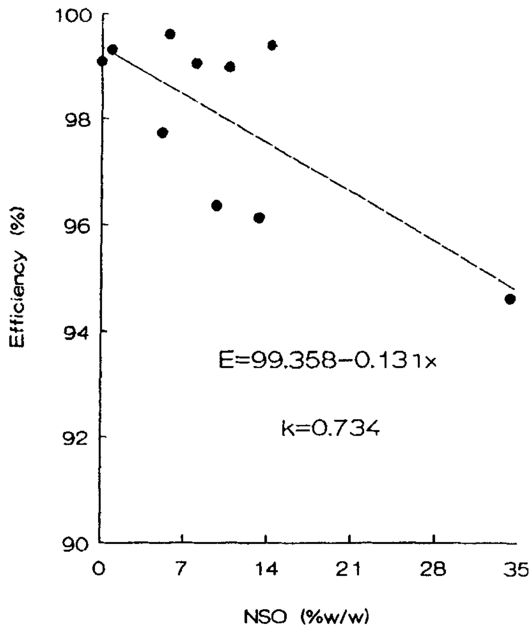

FIG. 12 Dependence of coalescence efficiency on the NSO compounds content in DP.

Coalescence efficiency exhibits a decreasing dependence on mean molecular weight (Fig. 8) and neutralization number (Fig. 9). It seems plausible to suppose that higher mean molecular weights are a consequence of the presence of carboxylic groups (high values of neutralization number) which, due to their polar nature, could hinder coalescence. However, to the best of our knowledge, there are no analogous data with which to make a direct comparison.

In contrast to the possible effect of polar carboxyl groups, the increasing content of nonpolar alkanes has a favorable effect on the coalescence efficiency, giving a linear correlation with a high regression coefficient of 0.971 (Fig. 10). It can be postulated that chain molecules increase the probability of collision, a situation similar to the effect of flocculants in water treatment (13).

Our studies of coalescence efficiency as a function of aromatics content (Fig. 11), and NSO compounds (Fig. 12) gave only a weak correlation. Although the dependences presented have been chosen on the basis of the largest regression coefficient, even their trends are questionable. Similar findings have also been obtained for the effect of vapor components and asphaltenes.

On the bases of the above results, we derived the general mathematical model given by the following equation:

$$E = 3232\Delta\rho^{-0.25}\mu^{0.05}M^{-0.39}Nb^{0.071}(G_{n-\mathrm{a}})^{0.061}(G_{\mathrm{ar}})^{-0.125} \quad (2)$$

The presented model may be useful in assessing the possibility of oil separation from formation water on the basis of selected oil characteristics.

CONCLUSIONS

In the present study we examined the effects of a number of characteristics of oil as the dispersed phase on coalescence efficiency in bed coalescence. In addition to the parameters studied by other authors, we included several parameters (mean molecular weight, neutralization number, content of *n*-alkanes, aromatics, and NSO compounds) which, as far as we know, have not been studied previously. The general model derived on the basis of individual effects could be useful in assessing the possibility of oil separation from formation water.

ABBREVIATIONS

WO/O4	bed coalescer
NSO	nitrogen, sulfur, oxygen compounds
DP	dispersed phase
EPS	expanded polystyrene granules
PU	polyurethane foam
A–G	marks of crude oil samples
I–III	oil fractions samples
DMA...	model emulsion

SYMBOLS

E	separation efficiency (%)
C_0	oil content in influent (mg/L)
C_e	oil content in effluent (mg/L)
ρ	oil density (kg/m^3)
$\Delta\rho$	density difference (kg/m^3)
μ	viscosity (m·Pa·s)
M	mean molecular weight (kg/mol)

Nb	neutralization number (mg KOH/L)
$G_{n-\mathrm{a}}$	content of *n*-alkanes (% w/w)
G_{ar}	content of aromatics (% w/w)

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