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Effect of Working Conditions on Bed Coalescence of an Oil-in-Water Emulsion Using a Polyurethane Foam Bed

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An oil-in-water emulsion was separated by bed coalsecence using polyurethane foam chips as the filter media in a steady-state regime, including gravity settling. A study was made of the effect of working conditions such as fluid velocity, bed length, and influent oil content on the effluent oil concentration and separation efficiency. Model emulsions were prepared by mixing the vacuum fraction of naphthenic-base oil and water to obtain a mean droplet diameter of about 20 μm. All experiments were carried out at a constant temperature of 20 °C. The range of the influent oil concentration was from 500 to 2000 mg L^{-1}, the range of the fluid velocity from 10 to 45 m h^{-1}, and the range of the bed length from 3 to 15 cm. The obtained effluent oil concentration was from 3.12 to 138 mg L^{-1}, and the separation efficiency was 82.0−99.8%. Empirical equations were derived describing the coalescence efficiency and effluent concentration as a function of bed length, influent concentration, and fluid velocity.

Introduction

Emulsion flow through porous media may be broadly classified according to the emulsion stability and the ratio of drop size to pore size of the medium. In the case of oily wastewater, we have a dilute, relatively unstable emulsion flowing through the porous bed with the drop size smaller than the pore size, involving three simultaneous regimes of oil flow: oil droplets suspended in the aqueous phase, coalesced oil forming a continuous phase and flowing through well-connected channels, and the held-up oil as discrete coalescing globules that act as an intermediate between the dispersed oil and the continuous oil phase (Spielman, 1968, 1973; Spielman and Goren, 1970, 1972; Spielman and Su, 1977). In the case of stable emulsions, droplets deposit as a monolayer on the solid surfaces and the process of flowing is of a different character (Soo and Radke, 1984).

Other factors affecting emulsion flow through porous media are wettability, fluid velocity, and the surface chemistry of the drops and the porous matrix (Soma and Papadopoulos, 1995; Šećerov Sokolović et al., 1996).

Fluid velocity (v) plays an especially important role in emulsion flow as it controls the capture mechanism and capture probability of droplets, the distribution of dispersed phase per each of the three regimes of oil flow, and the breakup of the retained oil. Some authors define the critical velocity (v^*) as the velocity at which the effluent concentration of the dispersed phase exceeds a fixed value (Sareen et al., 1966; Spielman, 1968; Grilc et al., 1984, 1986). The same purpose serves the ratio v/v^* introduced by Rege and Fogler (1988). The critical velocity defines the maximum value of the working velocity to be employed in the bed coalescer, and it is of crucial importance for the design of the coalescer.

There are opinions (Spielman, 1968; Sherony and Kintner, 1971) that the influent concentration has no effect on the degree of coalescence and the filtration coefficient and that droplet size is much more important. In contrast to this, Patel (1975) showed that the efficiency decreases continuously with increasing the influent oil content in the range 100−300 mg L^{-1}.

The above authors have also investigated the role of the bed length in bed coalescence. They concluded that an increase in bed thickness yields an increased degree of coalescence, which is understandable as the total volume and contact surface are thus enhanced.

The majority of the works in the field are concerned with a nonsteady regime, characterized by a pressure drop with time, which corresponds to the conditions of deep bed filtration. However, for the coalescer design, knowledge of the steady-state separation performance, as it depends on the system's variables, is of primary importance.

Our previous investigations showed that polyurethane foam is an advantageous bed material, exhibiting a high separation efficiency in oily water treatment (Sokolović et al., 1992). Hence, the aim of this study was to find quantitative relationships between the fluid velocity, bed length, and influent concentration with the effluent concentration and separation efficiency for the polyurethane (PU) bed under the steady-state conditions. For this purpose, we chose the oil-in-water system as the model of unstable emulsion.

Equipment and Operating Procedure

The experimental bed coalescer was a horizontal tube (1), 1 m long, i.d. 0.05 m (Figure 1). The bed was located only at the inlet part of the tube (2), the rest being the space for settling out. The emulsion was prepared in two tanks (3) of 80 L each, by continuous stirring of the content with a stainless steel impeller (4), to obtain a mean droplet diameter of about 20 μm. The working temperature was 20 °C. The emulsion of constant influent concentration (C_i) was continuously forced through the bed by a membrane dosage pump (5) for all eight chosen fluid velocities (10, 13, 16, 19, 30, 35, 40, and 45 m h^{-1}). A selected velocity was kept constant for 1 h, and composite samples were taken in the last 15 min. The settled oil was discharged discontinuously through the valve (6). The experiments were carried out in a steady-state regime, which was achieved by preoiling the polyurethane foam chips. In this way, a

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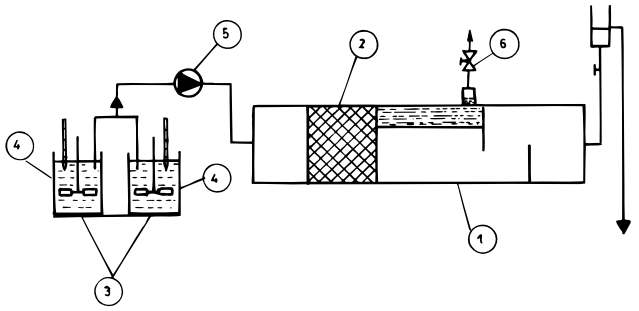

Figure 1. Schematic diagram of the experimental bed coalescer: 1, coalescer body; 2, filter medium; 3, tanks; 4, stainless steel impellers; 5, pump; 6, valve for oil discharge.

Table 1. Some Characteristics of PU of Different Bulk Densities

parameter	PU-1	PU-2	PU-3	PU-4
density, kg m^{-3}	1200	1200	1200	1200
bulk density, kg m^{-3}	50	90	140	180
bed porosity	0.96	0.92	0.88	0.85
permeability, 10^{-9} m^2	48.3	7.7	5.1	4.6
efficiency under the same conditions, %	99.6	99.0	98.6	98.3

steady state is established from the very beginning of the experiment, which was confirmed by monitoring the pressure drop, which did not change with time. The oil concentration was determined by IR spectrometry from a carbon tetrachloride extract. The oily water samples were maintained by adding HCl to obtain pH 2. The influent oil contents were 500, 800, 1100, 1400, and 2000 mg L^{-1}, and the bed length was 3, 5, 7, 10, and 15 cm.

The coalescence efficiency was calculated on the basis of the oil content in the influent (C_i) and effluent (C_e), using the expression

$$E(\%) = [(C_i - C_e)/C_i] \times 100 \qquad (1)$$

Properties of the Filter Media and Oil Phase

The characteristics of several PU foam samples are presented in Table 1. As PU is a compressible material, its bed properties are essentially dependent on the bulk density. Namely, an increase in bulk density diminishes the bed porosity and, thus, its permeability, the consequence being a decrease in coalescence efficiency. On determining the efficiencies of all PU samples at the same emulsion concentration, working velocity, and temperature, we chose as best a bulk density of 50 kg m^{-3}, and all experiments presented in this work were carried out using this bed material. The dimensions of the pore, microstructure, and surface morphology of the polyurethane foam were investigated by scanning electron microscopy (SEM). Gold-coated samples of pieces were prepared for the microscope in vacuum by a standard procedure. The pore channels of the polyurethane foam were of hexagonal shape with a mean diagonal of about 50−60 μm.

A naphthenic-base vacuum fraction, true boiling point 350−400 °C, was used as the dispersed phase. Its main characteristics were as follows: density at 20 °C, 844.73 kg m^{-3}; mean molecular weight, 349 g mol^{-1}; viscosity at 35 °C, 21.73 mPa s; neutralization number, 0.229 mg of KOH L^{-1}; pour point, −30 °C.

Results and Discussion

Some typical results obtained for the dependence of the effluent concentration on the fluid velocities for three chosen influent concentrations (mg L^{-1}), 500 (C_1), 800 (C_2), and 2000 (C_5), and a bed length of 15 cm are presented in Figure 2. As can be seen, when all other relevant variables are kept constant, the oil content in the effluent is a function of the flow rate and the influent oil content. The exponential form of the dependence is in agreement with data published in the literature. The breaks on the curves correspond to the v^* values. For each particular case, the critical velocity was determined by means of graphical extrapolation, and the results for all experiments are given in Table 2. The mean critical velocity obtained was 30.32 m h^{-1}. The maximal value was obtained for the smallest influent oil content and biggest bed length, and it amounted to 38.00 m h^{-1}, whereas the smallest value, obtained at the highest influent concentration and smallest bed length, was 23.40 m h^{-1}. At velocities below the critical one, the effluent concentration depends only a little on the fluid velocity. On the other hand, under the conditions of fluid velocities exceeding the critical value, the oil-phase concentration in the effluent is enhanced as a consequence of an increase in the ratio of small droplets passing the bed unchanged. In this case, either the coalescence has no time to take place, or small droplets are breaking up from the continuous oil phase under the influence of hydrodynamic forces.

As for the separation efficiency, we can identify a linear dependence on the fluid velocity. In all cases, the separation efficiency decreases with increasing fluid velocity. The range of the obtained values was from 97.0 to 99.7%.

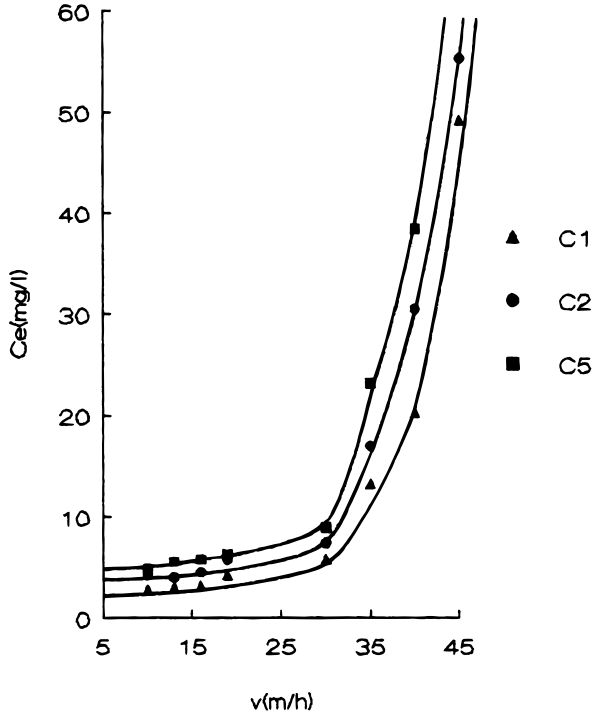

Figure 2. Dependence of the effluent oil concentration on fluid velocity for different influent concentrations (mg L^{-1}) of 500 (C_1), 800 (C_2), and 2000 (C_5) and fixed bed length of 15 cm.

Table 2. Critical Fluid Velocities Obtained for All Working Conditions

C_i	$L = 3$	$L = 5$	$L = 7$	$L = 10$	$L = 15$
500	26.60	37.90		30.20	38.00
800	25.60	32.00	27.50	30.00	36.00
1100	24.10	32.00	27.0	30.50	36.00
1400	24.70	30.00	28.00	30.20	36.00
2000	23.40	29.00	28.00	30.00	35.00

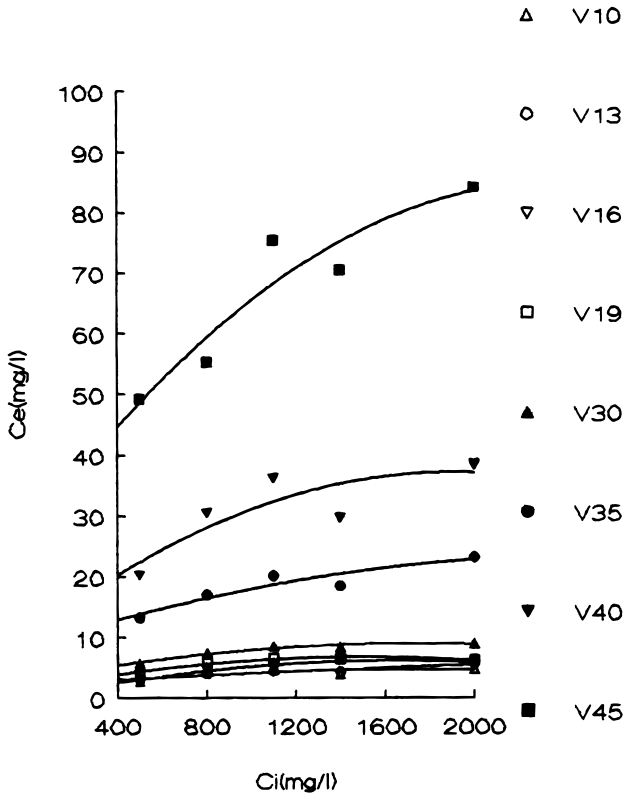

Figure 3. Dependence of the effluent concentration on influent concentration for different fluid velocities (v) from 10 to 45 m h^{-1} and fixed bed length of 15 cm.

As can be seen from Figure 3, the type of dependence of the effluent on the influent concentration is determined by whether the working velocity is below or above the critical one. If the working velocity is smaller than the critical one, the effluent concentration is practically independent of the influent concentration (curves v10−v30), as have already been reported in the literature (Spielman, 1968; Sherony and Kintner, 1971). In the other case, when the working velocity exceeds the critical value, the effluent concentration increases with the influent concentration, and the more so, the higher the working velocity (curves v35−v45), analogous findings being reported by Patel (1975). The presented curves were obtained for a bed length of 15 cm, and analogous results were achieved for all other bed lengths. Thus, our experiments show that both opinions may be right, depending on the range of fluid velocities employed.

Similarly, in the range of small fluid velocities, the separation efficiency is independent of the influent concentration, whereas at higher working velocities, significantly lower efficiency is obtained.

In view of the above, it was interesting to consider simultaneous effects of the working velocity and influent concentration, by presenting them in the form of a 3D diagram (Figure 4). As can be seen, there are two ranges in which the effluent concentration is independent and significantly dependent of both the fluid velocity and the influent concentration, the divide being the critical velocity.

The dependence of the effluent concentration on bed length is illustrated in Figure 5. The presented curves were obtained for the constant influent concentration of 800 mg L^{-1}, similar findings being obtained for all other concentrations. As in the above cases, it is also possible to distinguish two regions of working velocities

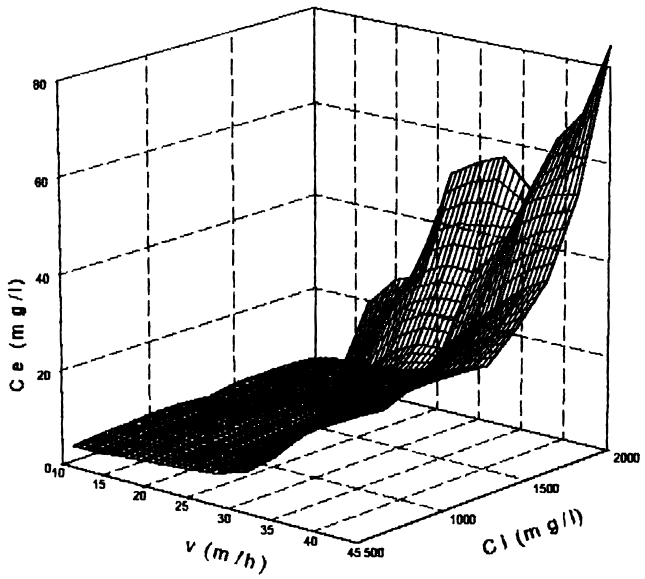

Figure 4. Three-dimensional diagram representing the interdependence of the effluent concentrartion, fluid velocity, and inlet concentration for a fixed bed length of 15 cm.

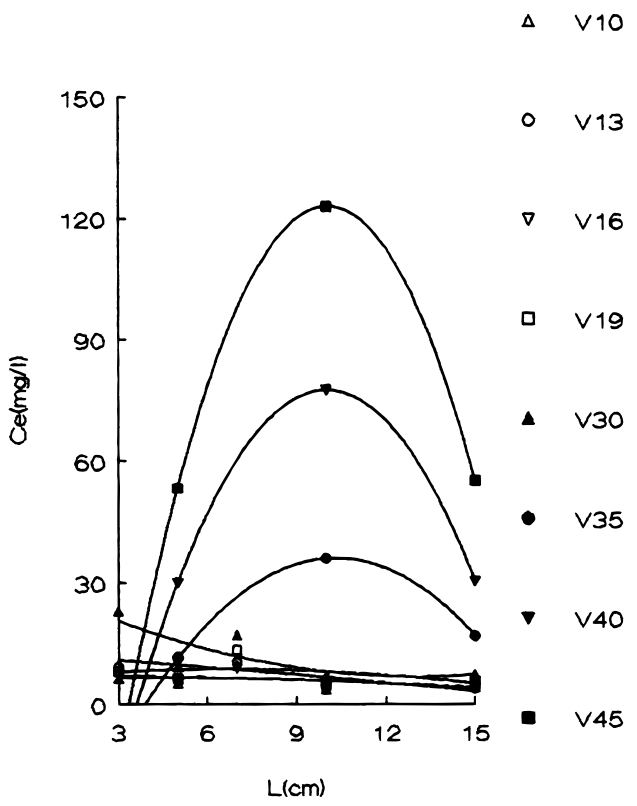

Figure 5. Dependence of the effluent concentration on bed length for different fluid velocities (v) from 10 to 45 m h^{-1} and the influent concentration of 800 mg L^{-1}.

with v^* as a bordering value. For the range of bed lengths employed, the dependence of the effluent concentration on bed length for $v < v^*$ is almost negligible. On the other hand, for $v > v^*$, a maximum of the effluent concentration (minimum of the separation efficiency) is obtained for a bed length of 10 cm.

As far as we know, there are no such apparently anomalous observations described in the literature. One of the main reasons for this situation may be the fact that the working parameters used by other authors did not fall into the range used in our experiments. It should be pointed out that in our case, the curves

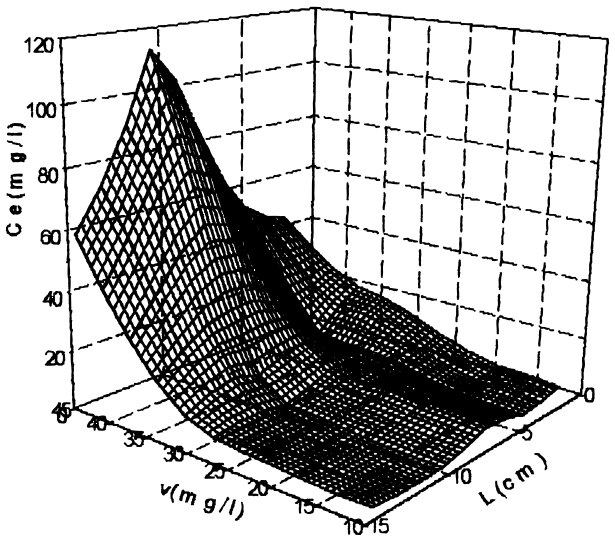

Figure 6. Three-dimensional diagram representing the interdependence of the effluent concentrartion, fluid velocity, and bed length for the influent concentration of 800 mg L^{-1}.

obtained at velocities exceeding the critical value exhibit a surprising trend, as the bed length exerts an unexpected effect. The fact that approximately equal efficiency was obtained for $L = 7$ and 15 cm (with a minimum at $L = 10$ cm) suggests the processes of redispersion and repeated coalescence take place, and the bed acts as if it was composed of two beds. Namely, the oil drops enlarged by coalescence while passing through the remaining part of the bed are redispersed, and the smaller droplets thus formed may coalesce again, the situation being analogous to the one which would be obtained if there were two beds. Had only redispersion taken place, the effluent concentration would increase, but this increase would not occur if the drops underwent another coalescence.

Simultaneous effects of the fluid velocity and bed length, as well as the existence of the above maximum, are best seen from the 3D diagram presented in Figure 6.

A simultaneous dependence of the effluent concentration (g m^{-3}) on all three investigated variables, the fluid velocity (m h^{-1}), the influent concentration (g m^{-3}), and the bed length (m), can be described by the following empirical equation, obtained using linear multiple regression:

$$C_e = 0.0092 v^{0.774} C_i^{0.446} L^{-0.512} \qquad (2)$$

with a corresponding regression coefficient of 0.7873.

The analogous equation for the separation efficiency (%) is of the form

$$E = 99.16 v^{-0.0067} C_i^{0.0044} L^{0.004} \qquad (3)$$

with a regression coefficient of 0.7209.

These equations give the possibility of predicting the values of the effluent concentration and separation efficiency for a given set of all three variables. They may also be useful for adopting the working parameters for a given concrete situation of using the coalescer for oily water treatment.

The validity of eq 2 is illustrated in Figure 7, presenting the dependence of the calculated effluent concentrations on the experimental ones. As can be seen, the calculated and experimental values show a relatively good agreement.

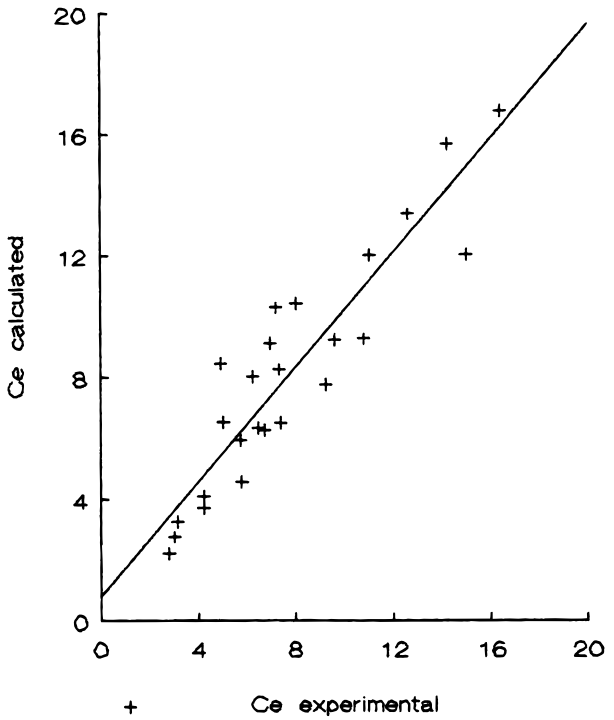

Figure 7. Relationship between the calculated and experimental values of the effluent concentrations.

Conclusion

The effect of the influent concentration and thickness of the polyurethane filter bed in the investigated range of variables on the effluent concentration and separation efficiency in a steady-state regime is negligible for the fluid velocities below the critical one. When the fluid velocity exceeds its critical value, the influence of concentration and bed length is changed. The increase in the influent concentration causes an increase in the effluent concentration, the more so the higher the fluid velocity. The obtained empirical equations may serve to choose the working parameters, ensuring a desired effluent concentration and separation efficiency.

Nomenclature

E = separation efficiency (%)
v = fluid velocity (m^3 h^{-1})
v^* = critical fluid velocity (m^3 h^{-1})
C_e = effluent oil concentration (ppm)
C_i = influent oil concentration (ppm)
L = bed length (m)
PU = polyurethane foam
PU-1, PU-2, ... = polyurethane foams with different bulk densities (kg m^{-3})

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