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ARTICLE *in* INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH · MAY 2003

Impact Factor: 2.59 · DOI: 10.1021/ie020361i

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Effect of Fibrous Bed Permeability on Steady-State Coalescence

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The effect of fibrous bed permeability on the efficiency of steady-state coalescence was investigated. Bed permeability was changed by compression of polyurethane fibers. The effect of bed permeability was followed based on the effluent oil concentration and critical velocity. An oil-in-water system was used as the model of unstable emulsion, with the drop size smaller than the pore size of the fibrous bed in all experiments. Different fluid velocities, bed lengths, and fluid-flow orientations were applied. The results indicate the existence of two regions of dependence, with a break point at a defined range identified as a critical one. Empirical equations were derived by describing the effluent concentration and critical velocity as a function of the bed permeability and length.

Introduction

Bed coalescence is a very complex phenomenon involving the effects of a large number of parameters. The efficiency of the operation depends on the bed characteristics, emulsion properties, emulsion interaction with bed material, and working conditions. Depending on the type of porous medium, the bed porosity may vary from near zero to almost unity. Fibrous beds are highly porous media. Because fibrous media are not as common as granular materials, they have been studied less extensively and therefore are much less understood concerning the correlation of resistance and the structure of the medium. The high-porosity bed geometry is extremely influenced by the fiber characteristics, their size, concentration, and arrangement. On the basis of the geometrical model of the fibrous bed, it could be assumed that in a significant portion of the pore space the fluid is not flowing. Permeability is a natural choice to express the flow resistance of a fiber bed.[1,2]

Some of literature data indicate the possibility of successful application of a fiber bed for liquid−liquid separation of both types of emulsion, water-in-oil and oil-in-water.[3−6] However, a systematic approach to the complex bed coalescence phenomena is still lacking, especially concerning the effects of fiber bed characteristics and bed permeability on coalescence efficiency.

Sareen et al.[3] investigated the effect of cotton, dynel, glass polyethylene, polypropylene, Teflon, and mixed-fiber beds on steady-state coalescence of oil-in-water emulsions. They used different fiber sizes, from 8.85 to 46.5 μm, of "closely packed" fibers with different roughnesses and rigidities. However, from a theoretical point of view, comparison of the results is difficult because many fiber characteristics were changed at the same time (size, nature, and morphology of the bed material).

Spielman[4] studied the effects of the fiber diameter on the pressure drop, dispersed-phase saturation, relative permeability, and filter coefficient in two-phase fluid flow through porous filter media. He found that only geometrically similar fibers produce equal oil saturation, which has an especially important role in steady-state coalescence.

Hazlett[5,6] investigated the effect of the amount of glass fibrous material, the fiber size, and the arrangement of beds composed of two or more pads with different fiber diameters on water coalescence in fuel, in both unsteady- and steady-state regimes. Some of the presented results indicate that the coalescence efficiency depends on the airflow resistance of the bed to a certain break point, after which a plateau is reached. However, these results were not discussed in detail.

This paper is focused on the effect of the fiber bed permeability on steady-state coalescence of an oil-in-water system as the model of unstable emulsion. Polyurethane (PU) is an advantageous fiber bed material, exhibiting a high separation efficiency in oily water treatment.[7−10] Šećerov Sokolović et al.[8] and Šević[9] investigated the coalescence efficiency of a PU bed, with a constant bulk density of 50 kg m^{-3}, on 7 real formation waters and 10 models of oil-in-water emulsions under a constant fluid velocity of 7.2 m h^{-1}. The mean separation efficiency for model emulsions was found to be in the range of 96.10−99.30%.

Šećerov Sokolović et al.[10] pointed out the importance of encompassment of the broad velocity range in a coalescence efficiency investigation because two regions of dependence are bordered by a critical velocity as a break point.

Because PU is a compressible material, its bed properties could be widely varied and the bulk density and total bed surface could be changed over a broad range. In that way, a bed based on the fibers of the same size, nature, and morphology, but differing considerably in fiber concentration, could be formed, resulting in drastic changes of the bed permeability. The effect of bed permeability on the effluent oil content and critical velocity was followed under equal working conditions,

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10.1021/ie020361i CCC: $25.00
Published on Web 05/21/2003

with the drop size being in all cases smaller than the bed pore size.

Equipment and Operating Procedure

The experiments were performed on a laboratory-scale bed coalescer, consisting of two sections, bed and settling sections, with the details being published in our previous paper.[10] Three possibilities of fluid-flow orientation were followed: horizontal (H), vertical downward (VD), and vertical upward (VG). The bed consisted of PU chips. The model emulsion, of a constant oil-in-water concentration, was prepared by continuous stirring with a stainless steel impeller in two tanks. The emulsion was continuously forced through the bed by a membrane dosage pump for all six chosen fluid velocities (16, 19, 30, 35, 40, and 45 m h^{-1}) used in experiments. A selected velocity was kept constant for 1 h, and composite samples were taken in the last 15 min in 5 min intervals. The working temperature was constant, 20 °C. The settled oil was discontinuously discharged through the valve at the end of the settling section.

A naphthenic-base vacuum fraction, through a boiling point of 350−400 °C, was used as the dispersed phase, at a concentration of 500 mg L^{-1}. The main characteristics of oil were a density at 20 °C of 844.73 kg m^{-3}, a mean molecular weight of 349 g mol^{-1}, a viscosity at 35 °C of 21.73 mPa·s, a neutralization number of 0.229 mg of KOH L^{-1}, and a pour point at −30 °C. The mean droplet diameter of about 20 μm was measured by an optical microscope. The interfacial tension, measured by the spinning drop interfacial tensiometer, model 500 Corexport, was 18.04 mN m^{-1}. The oil concentration in the effluent was determined by IR spectrometry from a carbon tetrachloride extract. Adding HCl to obtain pH 2 stabilized the oily water samples.

Five bed permeabilities defined by PU bulk densities of 50, 70, 90, 150, and 180 kg m^{-3}, marked as K_{01}−K_{05}, respectively, were used in the experiments. The bed permeability, K_0, was calculated from the measured pressure drop across the bed for sanitary water because data followed Darcy's law. The porosity of the bed was calculated based on the PU density and bed bulk density. Bed lengths of 3, 5, and 10 cm were applied for any permeability and all chosen fluid-flow orientations. A steady-state regime was achieved by preoiling the PU bed, with the pressure drop being constant with time during coalescence experiments.

Results and Discussion

Properties of the Bed. PU is a material with a different isotropic network. The PU bed used in this work has a double hexagonal channel shape. The pore size, microstructure, and surface morphology of the original PU chip were characterized by scanning electron microscopy (SEM).[9] Smooth fibers of triangular profile constitute the network of pore diameter in the range of 0.20−0.50 mm, depending on the bed bulk density as measured by optical microscopy. Experiments were realized in the broad range of bed properties (Table 1): permeability (5.34−0.18 10^{-3} mm^2), porosity (0.85−0.96), and solid surface (3.36−12.00 mm^{-1}). The solid surface is defined as a ratio of total surface area (mm^2) and bed volume (mm^3). The ratio of pore size to drop size was in the range of 10−25. The dependence of the bed porosity on bed permeability (Figure 1) defines in a proper way the bed characteristics in terms of bed geometry and resistance. Providing this relationship enables the reproductivity and comparison of bed coalescence experiments. Also, the results obtained in a broad range of bed bulk density or permeability values indicate the existence of a break point of dependence. The pronounced change of porosity of 0.85−0.93 corresponds to a permeability change in the interval of (0.18−1.13) × 10^{-3} mm^2 (break point), with only a slight change afterward, 0.93−0.96 for a permeability interval of (2.00−5.50) × 10^{-3} mm^2.

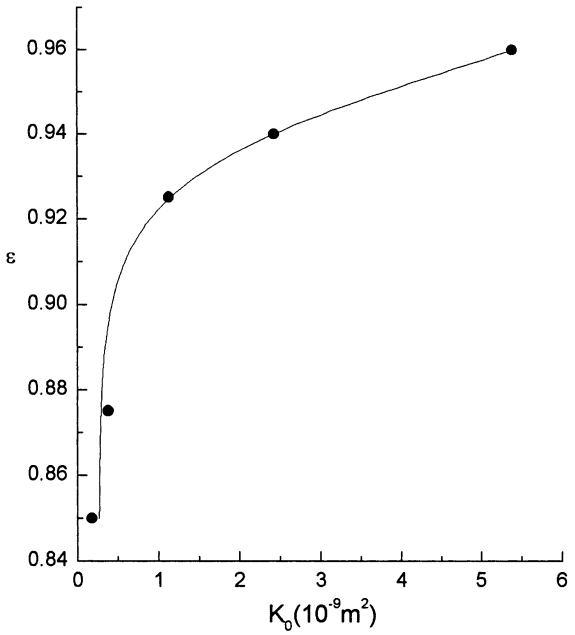

Figure 1. Dependence of porosity on bed permeability.

Table 1. Characteristics of a PU Bed of Different Bulk Densities

	bulk density, kg m^{-3}				
	50	70	90	150	180
hexagon diagonal, D, mm	0.50	0.40	0.30	0.25	0.20
fraction of solid, ϕ	0.04	0.06	0.08	0.13	0.15
porosity, ϵ	0.96	0.94	0.93	0.88	0.85
solid surface, S, mm^{-1}	3.36	4.64	6.00	10.0	12.0
permeability, K_0, 10^{-3} mm^2	5.39	2.43	1.13	0.38	0.18

Steady-State Bed Coalescence. The effect of bed permeability on the coalescence efficiency was followed based on the effluent oil concentration(C_e) and critical velocity (v_k). The critical velocity is defined as the velocity at which the effluent concentration of the dispersed phase exceeds a selected value, being defined as a maximal effluent oil concentration, in our experiments 15 mg L^{-1}, v_{k15}, corresponding to the break point of $C_e = f(v)$ curves.[10]

Some typical results of bed permeability effects on the effluent oil concentration are presented in Figures 2 and 3. The results are obtained using different velocities (Figure 2) for a bed length of 10 cm and H fluid-flow orientation, indicating the existence of two regions of dependence, with a break point at the defined bed permeability for each of the used fluid velocities. The pronounced effect of permeability is observed in the region below the break point, with the concentration reaching almost a plateau at higher permeability values. Simultaneous effects of bed permeability and fluid velocity, for a bed length of 5 cm and VG fluid-flow orientation, as presented in Figure 3 in a three-dimensional diagram, confirmed the existence of two

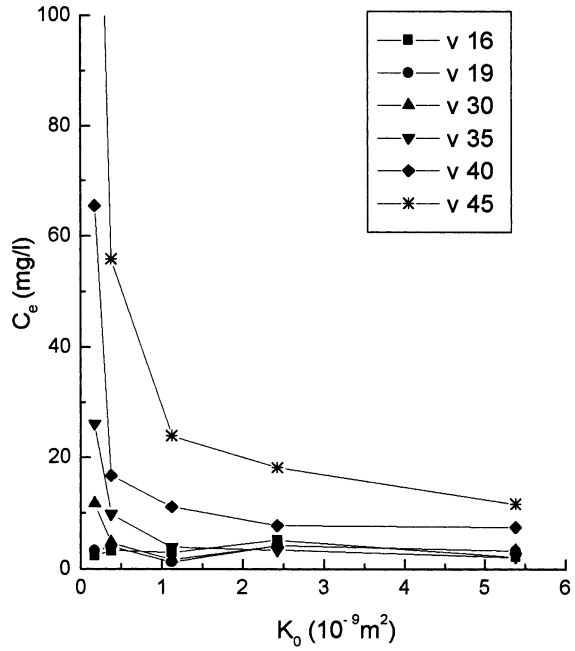

Figure 2. Dependence of effluent concentration on bed permeability for different fluid velocities and a fixed bed length of 10 cm and H flow.

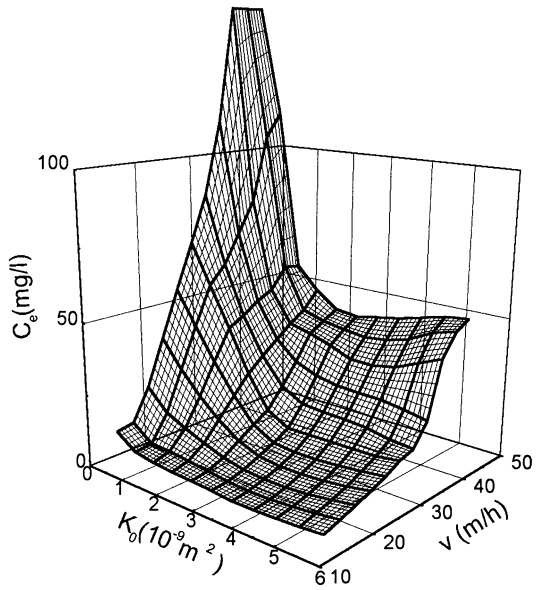

Figure 3. Three-dimensional diagram representing the interdependence of the effluent concentration, bed permeability, and velocity for a fixed bed length of 5 cm and VG flow.

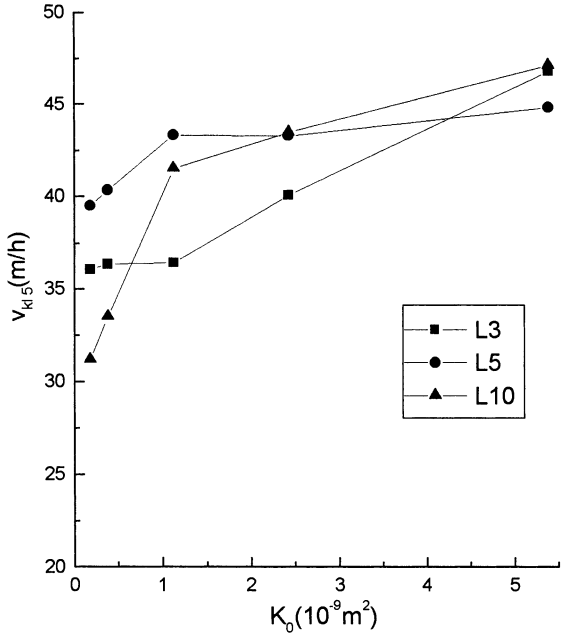

Figure 4. Dependence of critical velocity on bed permeability for different bed lengths and H flow.

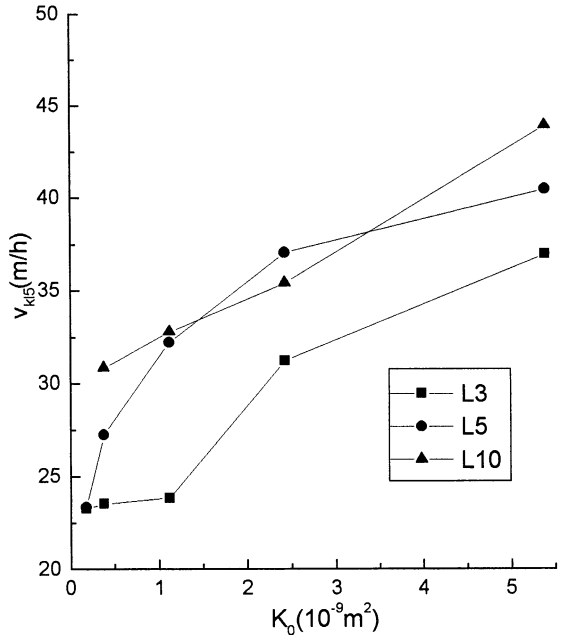

Figure 5. Dependence of critical velocity on bed permeability for different bed lengths and VD flow.

regions of dependence, especially pronounced for the high-velocity regime. Comparable results were obtained for all working conditions.

The break-point permeability could be considered as critical, K_{0k}, taking into account both the coalescence results and bed characteristics. Namely, the break point observed in the porosity/permeability curve (Figure 1) corresponds to the break-point range observed in coalescence experiments (Figures 2 and 3). The noticed phenomenon could be explained under the consideration that the drop capture in a steady-state regime is mainly determined by the quantity of saturated oil as drop coalescence takes place on its surface, being much less dependent on the available solid surface. Also, low permeability corresponds to a lower pore size (Table 1) and a reduced interconnected pore volume available for fluid flow, drastically increasing the interstitial velocity at the same overall working velocity. So, even at low working velocity, high local velocities contribute to the pronounced influence of hydraulic forces and therefore low coalescence efficiency. The coupled effect of a low quantity of saturated oil and high interstitial velocity contributes to a lower drop capture possibility, decreasing surface captures and capture time. Even, in the regime of high hydraulic forces, the possibility of inlet drop redispersion is increased together with an increase in the number of new drops detached from saturated oil, being smaller at high velocities.

The critical velocity, as defined previously, is of crucial importance for the coalescer design because it defines the limiting reasonable value to be applied for defined

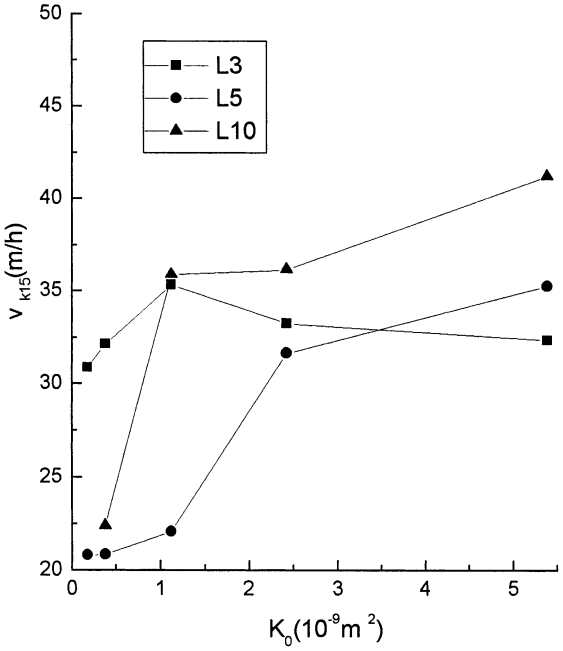

Figure 6. Dependence of critical velocity on bed permeability for different bed lengths and VG flow.

conditions. It should also be followed and defined in all experiments aiming to investigate mechanisms, phenomena, and practical issues because in that way the results from different experiments could be better correlated and understood. The critical velocity could be considered as a kind of dependent variable being influenced by the process parameters, and the investigation of this interdependence is of basic importance for experiment transparency and coalescer design.

The effect of bed permeability on the critical velocity, v_{k15}, for different fluid-flow orientations is presented in Figures 4−6. Generally, the critical velocity increases with increasing permeability under all applied working conditions, showing a break point at which the intensity of the dependence is considerably changed, corresponding to critical permeability, K_{0k}. Pronounced differences in the critical velocity, v_{k15}, are observed for the applied range of bed permeability, K_0. For H fluid-flow orientation, this range is 47.12−31.17 m h^{-1}, for VD it is 43.90−23.24 m h^{-1}, and for VG it is 41.20−20.81 m h^{-1}.

As mentioned earlier, low permeability values are not appropriate even at low working velocities. Because the critical velocity is defined as the highest value corresponding to the limiting concentration in the effluent, it is clear that the critical velocity region is drastically sensitive to both inlet and local velocities. Because it was shown that the changes in permeability cause the change of critical velocity in the interval of 50−100%, the permeability could be considered as a crucial factor for equipment size and therefore capital cost.

The results on the effects of the bed length on permeability (Figures 4−7) show the general increase of critical velocity values for the region above critical permeability, as expected. However, below the critical permeability, this trend is not consistent, indicating instability of the system.

Based on the experimental data, using linear multiple regression it is possible to establish some empirical equations useful for bed coalescer design. Equations 1 and 2 give the possibility of estimating the value range of the effluent concentration and critical velocity, respectively, for a given set of chosen variables:

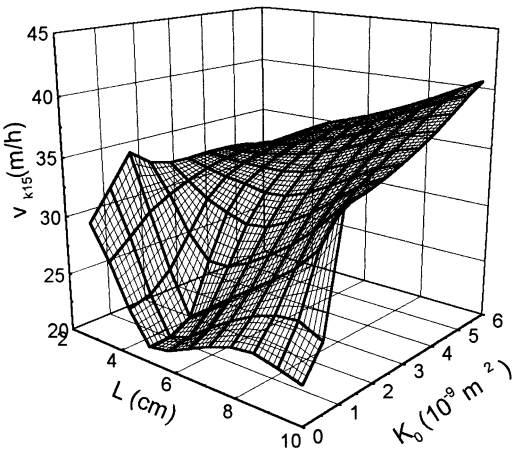

Figure 7. Three-dimensional diagrams representing the interdependence of critical velocity bed permeability and bed length for VG flow.

$$C_{eH} = 1.15 \times 10^{-4} v^{2.0816} L^{-0.0803} K_0^{-0.181} \quad (1)$$

The corresponding coefficient R for eq 1 is 0.785, and the standard error is 0.6635.

$$v_{k15H} = 168.18 L^{0.01928} K_0^{0.06611} \quad (2)$$

The corresponding coefficient R for eq 2 is 0.793, and the standard error is 0.0692.

On the basis of a comparison of the numerical values of exponents in eqs 1 and 2, it could be concluded that the bed permeability effect on the efficiency is more pronounced than the bed length, at least in steady-state coalescence.

Conclusion

The efficiency of a high-porosity fiber bed coalescer, with broad variations of bulk densities, is highly influenced by bed permeability only over a specific region. The region below some critical permeability value brings about the instability of the system, with low and unpredictable efficiency. The identification of the critical permeability value for each application and the defined bed material is advantageous for optimal equipment design.

Acknowledgment

The support of this work by Ministry of Science and Technology of Serbia is gratefully acknowledged.

Nomenclature

C_e = effluent oil concentration, mg L^{-1}
C_{eH} = effluent oil concentration for horizontal fluid-flow orientation, mg L^{-1}
D = hexagon diagonal of PU channels, mm
d_p = mean drop diameter, μm
K_0 = bed permeability, m^2
K_{0k} = critical bed permeability, m^2
L = bed length, m
v = fluid velocity, m^3 h^{-1}
v_{k15} = critical velocity for C_e = 15 mg L^{-1}
v_{k15H} = critical velocity for C_e = 15 mg L^{-1} for horizontal fluid-flow orientation
R = regression coefficient
S = solid surface, mm^{-1}

Greek Letters

γ = interfacial tension, mN m^{-1}
ϵ = bed porosity
μ = viscosity, mPa·s
ϕ = fraction of solid

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Resubmitted for review May 16, 2002
Revised manuscript received January 6, 2003
Accepted February 20, 2003

IE020361I