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SEPARATIONS

# Effect of Fluid Flow Orientation on the Coalescence of Oil Droplets in Steady-State Bed Coalescers

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The effect of prime fluid flow orientation on non-Brownian oil-drop steady-state coalescence in a high-porosity bed was investigated. This effect was analyzed via effluent oil concentration and critical velocity. Three fluid flow orientations were examined, namely, horizontal, vertical up, and vertical down, over a wide range of bed properties and working velocities, as well as three bed lengths. On the basis of the effluent oil concentration, the effect of flow orientation is dominantly determined by fluid velocity. It was concluded that the horizontal flow is most effective for a steady-state bed coalescer, over all working conditions.

## Introduction

The design and optimization of bed coalescers strongly depend on an adequate understanding and description of the emulsion transport through porous media, drop attachment, detachment, coalescence, and redispersion phenomena. Very often, fiber materials used in these units are waste polymers,[1] thus contributing also to environmental protection and sustainable development. Research has shown that fibrous media, with their high porosities (porosity range 0.85−0.99) can ensure higher separation efficiency than granular media (porosity range 0.30−0.50).[2] Despite the intensive decade-long research into their design and sizing, bed coalescers require further examination.

More than 30 years ago, Spielman[2,3] found that only geometrically similar beds produce equally dispersed liquid saturation in porous media. Drop capture in the steady-state regime mainly takes place on saturated dispersed liquid, rather than on the available solid surface. Therefore, the quantity of saturated liquid determines the coalescence efficiency. Spielman conducted his experiments with a downward flow fluid orientation.

Sareen and Hazlett[4,5] (frequently cited in the literature) carried out their experiments on a horizontal fluid flow. Chieu et al.[6] suggested an experimental unit with a vertical orientation for the investigation of bed coalescence, giving no explanation for such a choice. Perhaps, this most frequent type of bed orientation has been taken over from deep bed filtration.

As previously mentioned, it should be pointed out that, when comparing experimental results, many researchers have neglected fluid flow orientation. In our opinion, such an approach is not acceptable.

The literature search shows that only Burganos et al.[7−11] have addressed the problem of fluid flow orientation, but in the domain of deep bed filtration in a solid−liquid system. On the basis of their simulation, the importance of flow mode in this operation was explicitly pointed out. These results showed that the effect of flow mode is dominantly determined by the range of superficial velocity and bed heterogeneity.

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The objective of this work was to experimentally determine the influence of flow mode on steady-state high-porosity bed coalescence efficiency. We continued our studies[12,13] of simultaneously varying bed properties and fluid velocity over a wide range of values, to overcome frequent use of only discrete values.

## Equipment and Operating Procedure

**Experimental Setup.** The experiments were performed on three laboratory-scale bed coalescers (Figure 1): horizontal (H), vertical down (VD), and vertical up (VU) fluid flow. All setups consisted of two sections, the bed and the settling section (1, 2).

A model oil-in-water emulsion of constant oil concentration, 500 mg $L^{-1}$; constant temperature, 20 °C; and constant mean drop diameter (about 20 $\mu$m) was prepared in two tanks (3) by continuous stirring with a stainless steel impeller (4). The emulsion was continuously forced with a membrane dosage pump. The settled oil was discharged from the settling section discontinuously through the valve (6).

**Fibers and Bed Properties.** A compressible bed of smooth polyurethane (PU) fibers with different properties was used in the experiments. The microstructure, surface morphology, and size of the fibers were characterized by scanning electron microscopy (SEM). Optical microscopy was used to determine the pore diameters of different bed bulk densities and mean drop sizes.

Investigations were performed over a broad range of bed properties: permeability, $(5.39-0.18) \times 10^{-3}$ $mm^2$; porosity, 0.97−0.85; solid surface, 3.00−12.00 $mm^{-1}$; and ratio of pore size to drop size, 25−10 (Table 1). To obtain uniformity of the bed packing in the whole volume, small portions of fibers were packed one after another.

**Experimental Conditions.** The experiments were carried out in the steady-state regime, achieved by pre-oiling of the fibers. Therefore, the steady state was established from the very beginning of the experiment and confirmed by a constant pressure drop.

Bed length and bed permeability were constant in each experiment, and the velocity (range of 16−50 m $h^{-1}$) was kept

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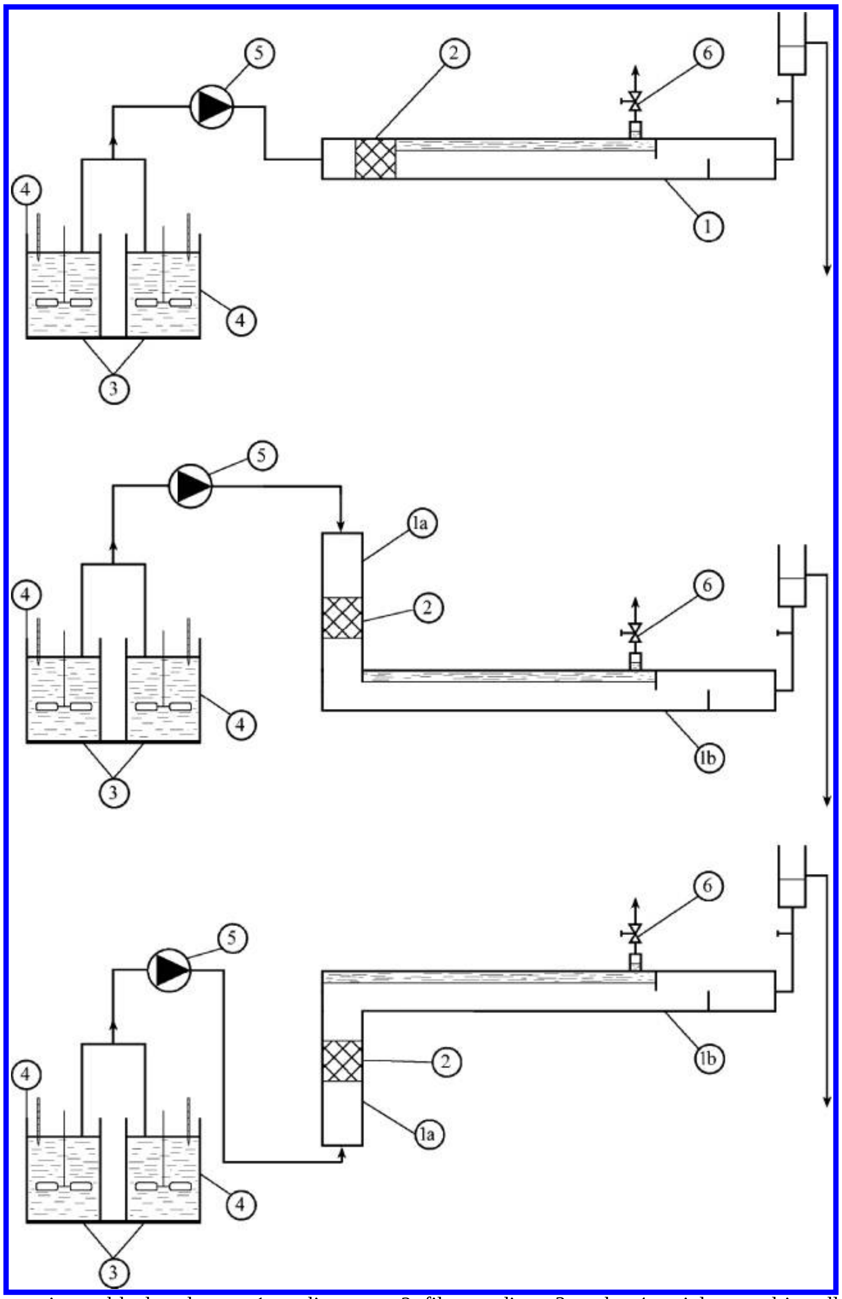


**Figure 1.** Schematic of the experimental bed coalescer: 1, settling zone; 2, filter medium; 3, tanks; 4, stainless steel impellers; 5, pump; 6, valve for oil discharge.

**Table 1. Characteristics of the Bed Material**

| material | $\rho$ (kg m$^{-3}$) | $d_f$ ($\mu$m) | $\epsilon$ | $S$ (mm$^{-1}$) | $K_0$ ($10^{-9}$ m$^2$) | $D_p$ ($\mu$m) | $D_p/d_d$ |
|---|---|---|---|---|---|---|---|
| PU | 1200 | 50 | 0.96 | 3.36 | 5.39 | 500 | 25 |
| | | | 0.94 | 4.64 | 2.42 | 400 | 20 |
| | | | 0.92 | 6.00 | 1.12 | 300 | 15 |
| | | | 0.88 | 10.00 | 0.38 | 250 | 12 |
| | | | 0.85 | 12.00 | 0.18 | 200 | 10 |

constant for 1 h. Composite samples were taken at the outlet of the settling section after 45 min at 5-min intervals. Three bed lengths (3, 5, and 10 cm) and five bed permeabilities (5.39, 2.42, 1.12, 0.38, and 0.18 $\times$ $10^{-9}$ m$^2$) were applied. The bed permeability, $K_0$, was calculated from the measured pressure drop across the bed using tap water. All data complied with Darcy's law. The porosity of the bed was calculated using the PU density and bed bulk density.

The oil concentration in the effluent was determined by IR spectrometry from a carbon tetrachloride extract, adjusted to pH 2 with HCl in order to stabilize the oily water samples.

**Properties of Dispersed Oil.** Naphthenic-base vacuum fraction (boiling point 350−400 °C) was used as the dispersed phase. The main oil 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; surface tension, 27.15 mN m$^{-1}$; and interfacial tension, 18.04 mN m$^{-1}$. Surface tension was measured with a stalagmometer, and interfacial tension was measured with a Corexport model 500 spinning drop interfacial tensiometer. Because polyurethane is a low-energy material with a critical surface tension of 23 mN m$^{-1}$, it is well wetted by oil.

## Results and Discussion

**Steady-State Bed Coalescence.** In porous beds, only unstable liquid−liquid emulsions can reach a steady-state regime because they form saturated liquid flowing through the well-connected bed channels. In the steady state, the surface of the saturated

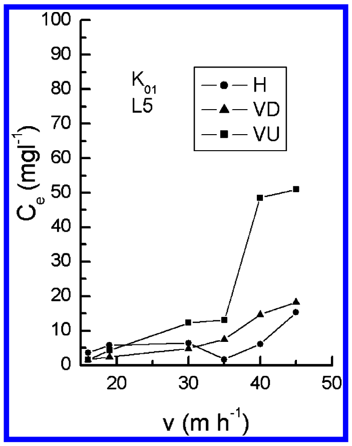


**Figure 2.** Dependence of effluent concentration on fluid velocity for a bed length of 5 cm and a bed permeability, $K_{01}$, of 5.39 × $10^{-9}$ $m^2$.

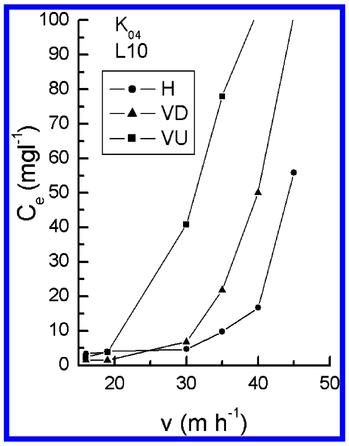


**Figure 3.** Dependence of effluent concentration on fluid velocity for a bed length of 10 cm and a bed permeability, $K_{04}$, of 0.38 × $10^{-9}$ $m^2$.

liquid is the place where drop coalescence occurs, determining coalescence efficiency. The saturation is dominantly influenced by fluid velocity and bed geometry.[2]

When the droplet size is smaller than the pore size, capture of the droplets involves all the known mechanisms, such as interception, sedimentation, hydrodynamic retardation, London–van der Waals attraction, Brownian diffusion, etc.

Because the London–van der Waals forces, adhesion, and double ionic layer forces are independent of working conditions, they can be omitted from the analysis of the effect of fluid flow orientation, taking into consideration only the forces of hydrodynamics, gravity, and buoyancy.

**Effect on Effluent Oil Concentration.** In the study of the effect of bed orientation on coalescence efficiency, three flow modes were used: horizontal, vertical down, and vertical up. The analysis was carried out using effluent oil concentration ($C_e$) and critical velocity ($v_{k15}$). The critical velocity was determined from the exponential dependence of the effluent oil concentration on the fluid velocity in each particular experiment. In this study, critical velocity ($v_{k15}$)[12] was determined at the point when the effluent oil concentration started to increase and reached 15 mg $L^{-1}$, because this value is often quoted as the tolerable level in oily water.

Some typical results on the effect of flow mode on the effluent oil concentration are presented in Figures 2 and 3. The results were obtained for the horizontal (H), vertical down (VD), and vertical up (VU) fluid flow orientations, using a wide range of fluid velocities (16–50 m $h^{-1}$), for bed lengths of 5 and 10 cm and bed permeabilities of 5.39 × $10^{-9}$ $m^2$ ($K_{01}$) and 0.38 × $10^{-9}$ $m^2$ ($K_{04}$), respectively.

The results show that the range of fluid velocity (hydrodynamic force intensity) determines the effect of the flow mode on the effluent oil concentration. For lower fluid velocities ($v$ < 35 m $h^{-1}$), the effluent oil concentrations in all three flow modes are very close. However, under these conditions, the intensity of the hydrodynamic forces is small, close to that of the other acting forces, leading to similar situations in all flow modes investigated. Consequently, similar effluent oil concentrations and separation efficiencies were expected.

Higher fluid flow velocities differentiate the effect of fluid flow orientation, resulting in a much lower effluent oil concentration for horizontal flow. The values of this concentration at the fluid velocity of 35 m $h^{-1}$ were in the range from 1.68 to 9.80 mg $L^{-1}$ for horizontal flow and from 13.20 to 78.00 mg $L^{-1}$ for upflow, depending on the bed length and bed permeability. The observed behavior can be explained on the basis of the analysis of the forces acting on the system.

It is well-known that forces are determined with their orientation and intensity. The gravity and buoyancy forces always act in the vertical plane. Their intensities are influenced by the drop size, the viscosity of the continuous phase, and the difference in density between the two liquids making the emulsion. Therefore, the orientation and intensity of the gravitational and buoyancy forces are independent of the fluid flow orientation and similar for all three flow modes investigated. The orientation of the hydrodynamic forces is similar to the main fluid flow orientation. Flow modes are differentiated solely by the orientation of the hydrodynamic forces. A high intensity of the hydrodynamic forces predominately influences the orientation of resulting forces.

In horizontal flow, the hydrodynamic forces push the saturated liquid from the bed in the horizontal direction, and at the same time, gravity and buoyancy forces tend to cause saturated liquid to be retained within the bed. The net effect, independent of the intensity of the hydrodynamic forces, tends to settle droplets exiting the bed. In addition, gravity and buoyancy forces concentrate the droplets within a few centimeters from the upper side of the flow pipe.[14] In this way, part of the dispersed phase is separated even before entering the bed. All of these effects, absent in both vertical flow modes, contribute to coalescence.

In vertical flow, all observed forces act in the same vertical plane, representing a one-dimensional system. Because oil is less dense than water, saturated oil tends to leave the bed. Additionally, in a vertical pipe with a dilute unstable oil-in-water emulsion, the droplets are uniformly distributed,[14] and consequently, there is no separation prior to the bed.

In the upflow mode (VU), hydrodynamic forces also tend to push saturated oil from the bed. When the intensity of the hydrodynamic forces reaches the intensity of both the London–van der Waals forces and adhesion, some of the saturated oil leaves the bed, decreasing the coalescence efficiency.

In contrast, in the downflow mode (VD), the hydrodynamic forces tend to keep saturated oil in the bed, thus increasing the bed coalescence and separation efficiency.

The differences in effluent oil concentration in Figures 2 and 3 can be explained as the effect of bed permeability.[12] The value of the bed permeability in Figure 3 is below the critical value; the pore diameters are small; the number of well-connected pores is smaller; and the interstitial velocity is increased, pushing part of the saturated liquid outside the bed.

**Effect on Critical Velocity.** As previously pointed out,[11,12] the critical velocity ($v_{k15}$) is the most appropriate quantity for the study of bed coalescence phenomena. It is of crucial importance for the optimal design of bed coalescers, because it

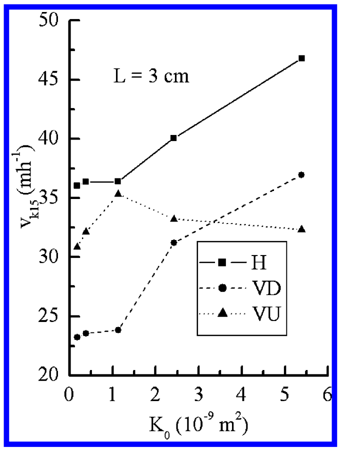


**Figure 4.** Dependence of critical velocity on bed permeability for a bed length of 3 cm and all flow modes.

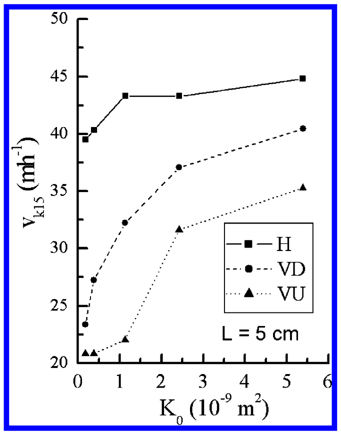


**Figure 5.** Dependence of critical velocity on bed permeability for a bed length of 5 cm and all flow modes.

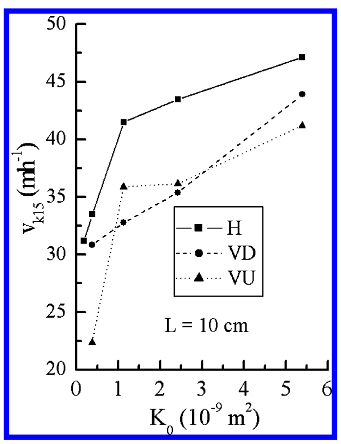


**Figure 6.** Dependence of critical velocity on bed permeability for a bed length of 10 cm and all flow modes.

defines the limits of the reasonable working velocity values for use in defined conditions.

The influence of the flow mode on the critical velocity is illustrated in Figures 4−6, presenting the dependence of the critical velocity on bed permeability for all three flow modes at bed lengths of 3, 5, and 10 cm. It is obvious that the maximum critical velocity was obtained for the horizontal flow mode over all working conditions, also in agreement with the effect of the flow mode on the effluent oil concentration at high fluid velocity.

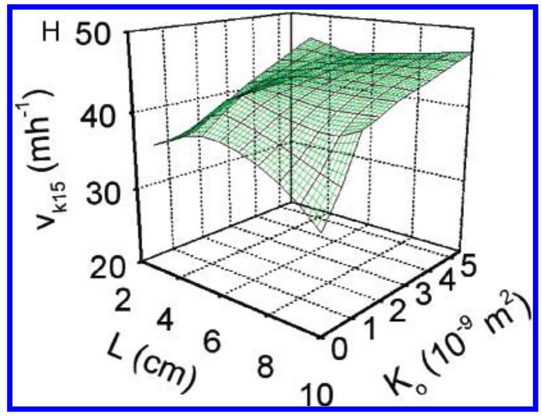


**Figure 7.** Three-dimensional diagram representing the interdependence of critical velocity, bed permeability, and bed length for the horizontal flow mode.

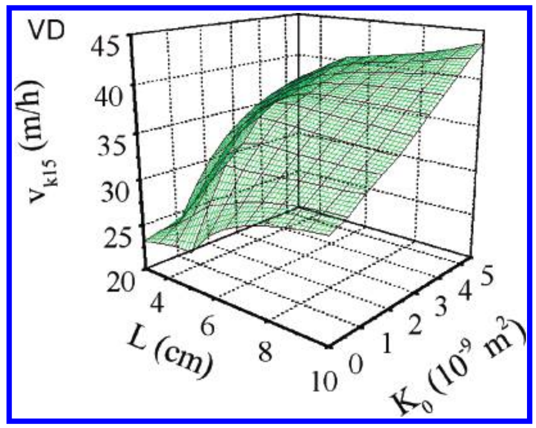


**Figure 8.** Three-dimensional diagram representing the interdependence of critical velocity, bed permeability, and bed length for vertical downward flow.

The critical velocity in vertical flows is significantly influenced by both the bed permeability and the bed length: it increases with increasing bed permeability, showing a break corresponding to the critical permeability, $K_{0k}$.[12] For the highest bed permeability optimal for bed operation, the vertical downward flow is always better than vertical upward flow, for all bed lengths investigated. At the highest bed permeability (the highest bed porosity and the largest pore size), the interstitial velocity decreases, causing an increase in saturated oil and, consequently, an increase in bed coalescence and separation efficiency.

Critical velocity is also influenced by the bed length, but this effect has to be considered in combination with the flow mode. The difference decreases between the vertical upward flow (the lowest efficiency) and the horizontal flow (the highest efficiency) with increasing bed length. This is illustrated by the values of the differences in critical velocities between the H and VU modes: 11.45, 8.84, and 5.95 m h$^{-1}$ for bed lengths of 3, 5, and 10 cm, respectively (Figures 4−6). This indicates that the effect of flow mode decreases with increasing bed length. This observation is even better illustrated in the 3D diagrams presented in Figures 7 and 8. As expected, such behavior is an outcome from two coupled effects, pore volume and contact time, both showing an increase with increasing bed length. A larger pore volume collects a larger quantity of saturated oil. The contact time is prolonged because the distance traveled through the bed length is longer. Thus, the increase in coalescence surface and contact time yields a significant increase in drop capture probability, i.e., separation efficiency.

## Conclusion

The separation efficiency of steady-state bed coalescence is highly influenced by flow mode.

On the basis of the effluent oil concentration, the effect of flow mode is dominantly determined by the range of fluid velocity. At high fluid velocities, horizontal flow bed coalescers are more efficient than vertical configurations, whereas at low velocities, there is no significant difference. At high fluid velocities, upflow operation is the least efficient.

If critical velocity is considered, horizontal steady-state coalescers have more advantages. The efficiency of vertical bed coalescers is more dependent on bed permeability and bed length. At the highest bed permeability, downflow coalescers are more efficient than upflow systems.

Critical velocity is also influenced by bed length. The differentiation in efficiency between flow modes decreases with increasing bed length.

## Nomenclature

$C_e$ = effluent oil concentration, mg $L^{-1}$
$d_f$ = fiber diameter, $\mu$m
$D_p$ = channel diameter, $\mu$m
$d_p$ = mean drop diameter, $\mu$m
$K_0$ = bed permeability, $m^2$
$K_{0k}$ = critical bed permeability, $m^2$
$L$ = bed length, cm
$S$ = solid surface, $mm^{-1}$
$v$ = fluid velocity, m $h^{-1}$
$v_{k15}$ = critical velocity for $C_e$ = 15 mg $L^{-1}$

*Greek Letters*

$\gamma$ = surface tension, mN $m^{-1}$
$\gamma_c$ = critical surface tension, mN $m^{-1}$
$\epsilon$ = bed porosity
$\mu$ = viscosity, mPa s
$\phi$ = fraction of solid
$\rho$ = density of polyurethane, kg $m^{-3}$

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