# Water-in-Oil Coalescence in Micro-Nanofiber Composite Filters

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*Coalescence filtration is very effective for the separation of secondary emulsions that contain water droplets with diameters less than 50 μm. The factors that control the performance of coalescer filter media are fiber size and wettability. High wettability materials for water-in-oil dispersion promote coalescence. New experimental results investigating the performance of nonwoven filter media glass fiber augmented with polymer nanofiber are presented in relation to the relevant parameters (wettability, filter depth, flow velocity, and filter materials). A decrease in fiber size improves the overall separation efficiency of the process. However, the nanofibers cause a significant increase in the pressure drop through the filter.* © 2004 American Institute of Chemical Engineers
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## Introduction

In recent years water-in-oil emulsion separation has received greater attention in the petroleum production. In many applications, dispersions of water drop sizes of less than 100 μm are very difficult to separate. The coalescence filter is economical and effective for the separation of secondary dispersions. There are three main steps of the coalescence process. First, the fibrous bed captures water droplets. Second, the collected droplets coalesce on the fibers. Third, the enlarged droplets migrate through the filter and are released from the fiber surfaces to be carried out of the medium by the oil flow. Coalescence performance depends on flow rate, bed depth, fiber surface properties, and drop size. Filter media with larger fiber contact areas per unit volume generally perform better than media with lesser surface areas.

The wetting behavior of the water-in-oil or oil-in-water emulsion significantly affects the performance of the liquid–liquid coalescence filter. Continuous, unwoven, woven, or chopped fibers of glass or polymers such as nylon and polyacrylonitrile (PAN) have increasingly important applications. Good wetting of fibers by the oil and water mixture and controlled fiber mixture interactions are necessary to obtain optimal composite mechanical properties (Schrader and Loeb, 1992). Many attempts have been made to determine the effect of the wettability on the coalescence process. However, investigators have different opinions of the effect of the wettability. Voyutskii et al. (1953) observed that an intermediate wettability gave the most effective separation, and concluded that, for the best performance, the filter should be sufficiently water-wetted to coalesce the water, but not so saturated as to produce excessive clogging by accumulated water. They found that the fiber contact surface is more important than pore size. Hazlett (1969a,b) reported that the water droplets in water-in-oil emulsions must displace the oil film from the wet fiber for attachment to be effective. A water droplet easily displaces oil on hydrophilic surfaces. The displacement on a low energy surface such as polyethylene or Teflon should be considerably less. However, Clayfield et al. (1985) showed that coalescence efficiency is not related to the wetting property of the continuous phase. They tested coalescence efficiency of seven different coated glass fibers and measured the critical surface tension.

There are three measures of filter performance that are of interest in this article and are summarized in Table 1. Capture efficiency $E$, is the most common measure, and is simply the ratio of mass (or number) of particles captured by a filter to the mass (or number) particles challenging the filter. It is related to the upstream and downstream concentrations by

$$E = 1 - \frac{C_d}{C_u} \tag{1}$$

**Table 1. Comparison Separation Efficiency *(E)*, Quality Factor *(QF)*, and Coalescence Efficiency *($\eta_c$)***

| Factors | Advantage | Disadvantage | Use |
|---|---|---|---|
| $E$ | Simple, Common use, direct evaluation of particle capture. | Does not account for pressure drop and hence does not account for filter thickness. | Can be correlated to compare overall capture efficiency. |
| $QF$ | Combines E and pressure drop to eliminate dependence on the filter thickness. | Assumes filter capture coefficient is not dependent on nonlinear mechanisms. | Used to compare media of different thicknesses and to optimize design. |
| $\eta_c$ | Accounts for the mechanism of coalescence. | In present form applies to monosized fibers. | Used for filter media of one fiber size. |

where $C_u$ is the number concentration (number count per unit volume) of water droplets upstream and $C_d$ is the number concentration of water droplets downstream (Akagi et al., 1990). The capture efficiency is often related to the individual fiber efficiency and to the filter coefficient (Brown, 1993).

Coalescing filter media also have the mechanisms of droplet drainage. Sherony and Kintner (1971a,b) define the overall coalescence efficiency, $n_c$ as a combination of capture efficiency and the fraction of collisions between drops that result in coalescence. The overall coalescence efficiency is exponentially related to the capture efficiency by

$$1 - E = \exp\left\{ - \frac{3(1-\varepsilon)S\left(1 + \frac{d_u}{d_f}\right)}{4d_f(1-S)}\,\eta_c L \right\} \tag{2}$$

where $\varepsilon$ is the void fraction of the clean filter, $L$ is the filter thickness, $S$ is the average saturation, $d_u$ is the upstream average water droplet diameter, and $d_f$ is the fiber diameter of the filter media.

Equation 2 was derived for a filter medium of one fiber size. It is not clear how to use this expression with composite media. Hence, we do not calculate $\eta_c$ for the composite media in this work.

The third way to characterize the filter performance is with the quality factor $QF$, defined as (Brown, 1993)

$$QF = \frac{-\ln\left(\frac{C_d}{C_u}\right)}{\Delta P} \tag{3}$$

For an idealized filtration of monodispersed particle size and uniform filter properties, the logarithm of the penetration $\ln(C_d/C_u)$ is proportional to filter thickness. Similarly, the pressure drop $\Delta P$ is proportional to filter thickness through Darcy's law. Hence, in principle, the $QF$ is independent of the thickness. To predict pressure drop, Sherony and Kintner (1971a,b) and Spielman and Goren (1972) developed mathematical models based on the Carman-Kozeny equation. The Carman-Kozeny equation was obtained on the basis that flow is laminar in the pores and that the pressure drop results entirely from the form-drag loss. Single and two-phase flows are discussed by Carman (1956) and can be expressed by the Carman Kozeny equations as follows

$$\frac{\Delta P_1}{L} = \frac{36U\mu K_1(1-\varepsilon_1)^2}{d_f^2\varepsilon_1^3} \tag{4}$$

$$\frac{\Delta P_2}{L} = \frac{36U\mu K_2(1-\varepsilon_2)^2}{d_f^2\varepsilon_2^3} \tag{5}$$

where subscript "1" refers to the single phase flow of the continuous phase, and the subscript "2" refers to the performance properties during two-phase flow conditions. $K$ is the Carman-Kozeny constant and $U$ is the superficial velocity.

From Eqs. 4 and 5, we can relate the void fraction in two-phase flow conditions to the pressure drops and Carman-Kozeny constants by

$$\frac{\Delta P_1}{\Delta P_2}\frac{K_2}{K_1}\frac{\varepsilon_1^3}{(1-\varepsilon_1)^2} = \frac{\varepsilon_2^3}{(1-\varepsilon_2)^2} \tag{6}$$

The void fraction in two phase flow is related to the average saturation $S$ by

$$S = 1 - \frac{\varepsilon_2}{\varepsilon_1} \tag{7}$$

where $S$ can be determined by mass balance on the dispersed phase.

Flow rate is an important factor in water-in-oil dispersion flow as it controls the capture mechanism and capture probability of droplets, and the distribution of the dispersed phase. Many attempts have been made to determine the critical velocity defined as the velocity at which the effluent concentration of the dispersed phase exceeds a fixed value (Sareen et al., 1966; Spielman, 1968; Fahim and Akbar, 1984; Othman et al., 1988; Šećerov Sokolović et al., 1997). Moses and Ng (1985) and Viraraghavan et al. (1997) observed that high operational temperatures are preferred for the coalescence process. Many results show that the separation efficiency is influenced by the filter bed depth. Hazlett (1969a) found that an increase in bed depth promotes coalescence, but there is a critical length beyond which the bed performance is not improved. Akbar and Othman (1989) show a relationship between liquid saturation profile and pressure drop and the optimum bed depth and the critical velocity. The saturation is defined as the ratio of the volume of liquid in the pores to the total pore volume. The local saturation profile reported by Akber and Othman decreases exponentially to a minimum value of saturation near the exit face of bed equivalent to the optimum height of the bed.

Low flow rates, high operating temperatures, and increased coalescer bed depth increase coalescence filtration efficiency. A decrease in the fiber diameter also improves the overall

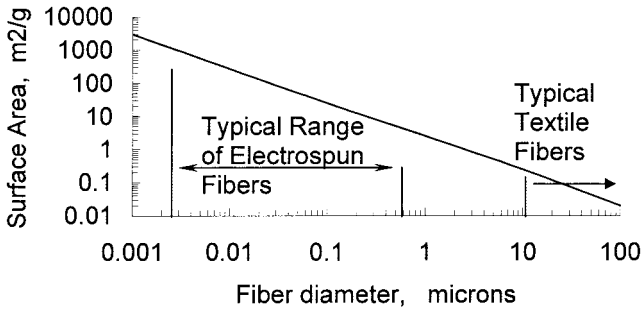


**Figure 1. Surface area per unit mass of fiber, calculated for Nylon 6 (density of 1,120 kg/m$^3$).**

The typical range for electrospun nanofibers have surface areas of about 5 to 1,000 m$^2$/g. A typical 10 micron textile fiber has a surface area of about 0.3 m$^2$/g.

efficiency of the filtration process. One of the important factors is surface area of the fiber. Surface area of the fibers, per unit mass, increases as the fiber diameter decreases.

To obtain smaller fiber diameters in the filter media, an electrospinning method is used to produce long polymer fibers with diameters in the range of 10–500 nm (Gibson et al., 2001). The electrospinning process is driven by the electrical forces on charges on the surface or inside a polymeric liquid. When the electric field reaches a critical value at which the repulsive electric force overcomes the surface tension force, a charged jet of the solution is ejected from the tip of a cone protruding from a liquid drop of the polymer. As the jet stretches and elongates in the air, the solvent evaporates, leaving behind a charged polymer fiber that lays itself randomly on a grounded collecting surface. Thus, continuous fibers are produced to form a nonwoven fabric (Doshi and Reneker, 1995). Nonwoven fibrous materials composed of electrospun fibers have a large surface area and a small pore size compared to commercial textiles, making them excellent materials for use in filtration applications (Deitzel et al., 2001). Figure 1 shows how the surface area per mass significantly increases as the fiber diameter decreases.

The objective of this work is to investigate the coalescence separation of water droplets in a water-in-oil mixture using glass fiber media and glass fiber supplemented with electrospun nanofiber media. The goal is to experimentally study the relationship between pressure drop across the bed and separation efficiency. The results are analyzed using separation efficiency ($E$), quality factor ($QF$), and coalescence efficiency ($\eta_c$).

## Experimental Procedures

The experimental apparatus is shown in Figure 2. A mixture of water-in-oil was used in the experiments, in which deionized water was dispersed in oil (Viscor 1487, Rockvalley Oil and Chemical Company). The oil (specific gravity = 0.83) is pumped from tank 1 by a peristaltic pump, at a constant flow rate through a mixing pipe (where the water drops are mixed with the oil), through the filter sample and into a settling tank and reservoir. The flow rate is controlled by selection of tube diameter size for the peristaltic pump. Flow rates obtained with the peristaltic pump (Masterflex, Model L/S EW-07543-60) are from 100 mL/min to 290 mL/min.

The water-in-oil emulsion is produced in the mixing pipe. The water is pumped by a syringe pump through a hypodermic needle into the middle of the mixing pipe through which the oil flows. The mixing pipe is a Plexiglas tube with a 1 mm inside diameter and 11 mm outside diameter. The mixing pipe is inserted into the flexible tube between the pump and the sample holder. A very fine water-in-oil emulsion, in which 98% of water droplets are less than 50 microns, is produced at the outlet of the hypodermic needle, due to the shear force created by the following oil phase.

The concentration of water and size of the droplets are controlled by changing the water flow rate using the syringe pump. To decrease the size of the water droplets, the oil flow rate can be increased or the internal diameter of the Plexiglas pipe can be decreased, thereby increasing the shear rate across the needle opening.

Volumetric flow rates for the syringe pump (WPI, Model Sp101i) are from 0.001 micro L/min to 1.175 mL/min. The water droplets produced in this way remain dispersed in the oil for an extended length of time, long enough to conduct the filtration experiments. The water droplets in the oil collide and coalesce with each other in the filter sample and form larger drops of water that are carried downstream to the settling tank. In the settling tank the larger drops are readily separated from the oil by gravity. Smaller drops that do not settle out by gravity are carried into the reservoir tank.

The filter holder is made of Plexiglas. Machined into the holder is a cylindrical 2.5 cm diameter opening for placement of the filter test sample. The filter samples fit snuggly in the opening and are positioned against a coarse stainless steel wire mesh screen fixed in the sample holder.

Liquid samples are taken through the two sampling points to measure the size distribution of water droplets at intervals of 10 to 25 min. The sampling points are positioned upstream of the filter holder and downstream of the settling tank. Simultaneously, the pressure drop across the filter is measured using a manometer. The pressure drop reaches steady state in about 10 min. After that time, coalesced water drops emerge from the filter in the effluent. The size distribution of water droplets are measured with a particle-size analyzer (Hyac Royco BR8).

### *Filter samples*

The properties of the filter media test samples used in this work are summarized in Table 2. The filter samples were made

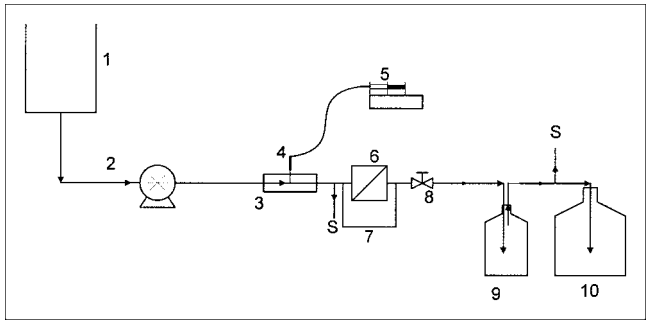


**Figure 2. Filtration experimental apparatus.**

(1) Oil Tank; (2) peristaltic pump; (3) mixing pipe; (4) hypodermic needle; (5) syringe pump; (6) filter sample holder; (7) manometer; (8) valve; (9) settling tank; (10) reservoir tank; (S) sampling points.

**Table 2. Physical Property of Filter Media**

| Parameter | Filter 1 | Filter 2 | Filter 3 | Filter 4 | Filter 5 |
|---|---|---|---|---|---|
| Added Nanofiber, mass, g | None | PAN | Polyamide | Nylon | None |
| | 0 | 0.0188 | 0.0141 | 0.0179 | 0 |
| Total filter mass, g | 0.18 | 0.24 | 0.22 | 0.24 | 0.32 |
| Filter Thickness, $L$, mm | 3 | 3 | 3 | 3 | 5 |
| Porosity, $\varepsilon_1$ | 0.940 | 0.962 | 0.973 | 0.985 | 0.940 |
| Area Ratio of Nanopolymer, % | 0 | 3.79 | 14.97 | 10.02 | 0 |
| Efficiency, $E$, % | 71 | 75 | 77 | 75 | 92 |
| Average Saturation, S | 0.019 | | | | 0.017 |
| Coalescence Efficiency, $\eta_c$ | 0.445 | | | | 0.072 |
| Quality Factor, $QF$, kPa$^{-1}$ | 2.25 | 1.02 | 1.03 | 0.80 | 3.93 |

of glass fibers supplied by Hollingsworth and Vose with no further treatment of the fibers. To make the samples, 0.5 grams of glass fibers are dispersed in 2 L of water and sulfuric acid (pH 2.5) and 2 mL of an acrylic binder solution (Carboset 560, BF Goodrich). The slurry is stirred 8 to 24 h. The slurry is vacuum filtered onto a fine mesh screen in a mold with an inside diameter of 2.54 cm to form the filter samples. The applied vacuum pressure is from 100 to 160 kPa. To make the composite filter of glass fibers and polymer nanofibers, the nanofibers are added to the slurry of glass fibers and the filter sample is prepared as mentioned above. While still moist, the vacuum molded filters are removed intact from the mold and dried in an oven for about 120 min at a temperature of 150°C. This heat treatment thermally sets the binder and forms a relatively rigid filter sample. The filter porosity is measured using a tailor made pycnometer.

### *Electrospinning*

Figure 3 shows the apparatus used in the electrospinning. The syringe is filled with polymer solution. The flow rate is controlled with a syringe pump (WPI, Model Sp101i). The needle with a 1.6 mm outside diameter and 1 mm inside diameter is connected to a power supply and charged to 20,000 volts (Gamma High Voltage Research, Model D-ES30PN/M692). The collecting surface is grounded to attract the charged fibers and placed about 20 cm from the tip of the needle.

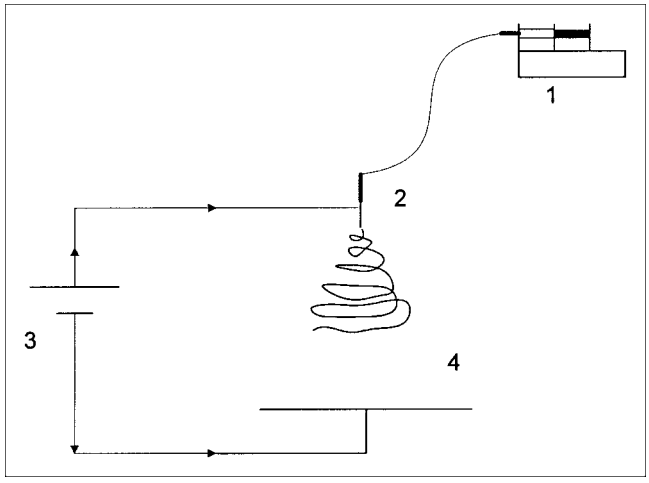


**Figure 3. Electrospinning apparatus.**

(1) Syringe pump; (2) hypodermic needle; (3) power supply, 20000 volts; (4) collecting surface.

Three polymers are used to make the nanofibers in this work. The Nylon solution is prepared by dissolving 16 wt. % Nylon-6 in 84 wt % Formic acid. Fibers of Poly(meta-phenylene isophthalamide) (Polyamide) are dissolved in N,N-dimethylacetamide (DMAc) containing 4% lithium chloride (LiCl) at 60°C to form a homogeneous solution with 16 wt % polymer solution. The polyacrylonitrile (PAN) solution is prepared by dissolving 12 wt % PAN in 88 wt % N,N-Dimethyl formamide at 80°C to form a homogeneous solution. Diameters of the fibers and specific surface areas of the fibers are provided in Table 3. Electrospinning concentration, quantity of polymer solution, and flow rate of the syringe pump are provided in Table 4.

### *Contact angle*

One method for characterizing the wettability of the fibers is the Wilhelmy method (MacRitchie, 1990). Another method for measuring the contact angle onto a fiber is by measuring symmetrical drops of liquid directly attached to a fiber and using analytical expressions relating drop length, drop radius, and fiber radius to the contact angle to determine the surface free energy (Schrader and Loeb, 1992). However, both of those methods are difficult to use on the polymer nanofibers due to their small size. We indirectly characterize the wettability by measuring the wetting of the surface coated with the fiber material. This allows us to compare between the material properties even though the effects of the small radii of curvature of the fibers is not taken into account.

Contact angles are used to predict wettability. The wetting tension $\tau$ is calculated by

$$\tau = \gamma_{LV} \cos \theta \tag{8}$$

where $\gamma_{LV}$ is the surface tension of the test fluid and $\theta$ is the contact angle at the liquid–vapor interface line (Vogler, 1998). A spin coater (Specialty Coating System, Model P-6000) is used for coating the surface of a glass slide. A small amount of

**Table 3. Fibers and Their Diameters (Rangarajan, 2001)**

| Parameter | Approximate Average Dia. | Specific Surface Area |
|---|---|---|
| Glass fiber | 1.5 $\mu$m | 1.21m$^2$/g |
| PAN nanofiber | 500 nm | 6.76m$^2$/g |
| Polyamid nanofiber | 150 nm | 22.6m$^2$/g |
| Nylon nanofiber | 250 nm | 14.3m$^2$/g |

**Table 4. Data of Electrospinning**

| Polymer Solution | PAN | Polyamide | Nylon |
|---|---|---|---|
| Concentration, wt. % | 12 | 16 | 16 |
| Quantity, $\mu$L | 100 | 100 | 100 |
| Syringe pump flow rate for electrospinning, $\mu$L/min | 21.4 | 3.6 | 3.6 |

polymer solution is applied on the rotating glass surface. Contact angles are measured by using a contact angle meter (Ramé-Hart, Inc., Model 100-00 Contact Angle Goniometer) and by calculating the slope of the tangent to the drop at the liquid–solid–vapor interface line.

## Results and Discussion

### *Effect of polymer nanofibers*

The main aim of this research is to investigate the effects of adding the polymer nanofibers to glass fiber media on filter media performance. Four different filter media are examined. Filter media and electrospinning data are summarized in Tables 2–4. The total volume of polymer solution used to make the nanofibers was constant at 100 mL. The plots of pressure drop for polymer nanofiber filters are shown in Figure 4. As the water-in-oil emulsion passes through the filter, the saturation of water captured in the media increases and the pressure drop increases steadily to a constant value. The results for the particle-size distribution of upstream of the filter and downstream of the settler are shown in Figure 5. The design of the settling tank may influence these results; hence, these results are compared between the experiments for relative performance.

The nanofiber filters had a better capture efficiency, but also had a higher-pressure drop. In these experiments Figure 6 shows that the increased surface area of the filter samples provides an improvement in the coalescence efficiency. The area ratio of nanofibers to glass fibers is defined by

$$\text{Area ratio} = \frac{A_{\text{nanofiber}}}{A_{\text{glassfiber}}} \tag{9}$$

where the areas of the fiber are calculated by

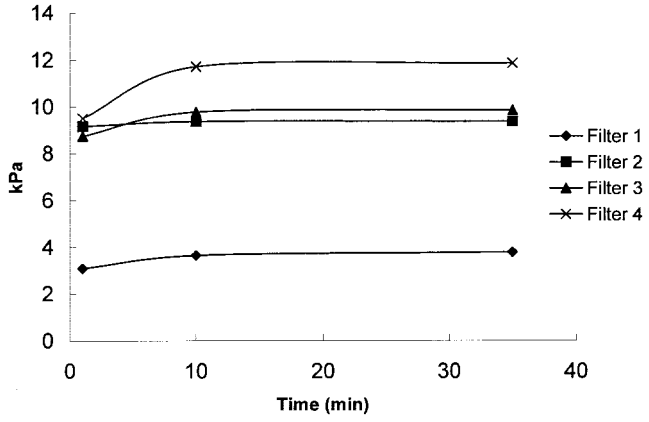


**Figure 4. Pressure drop vs. time for the filter media 1 to 4 listed in Table 2.**

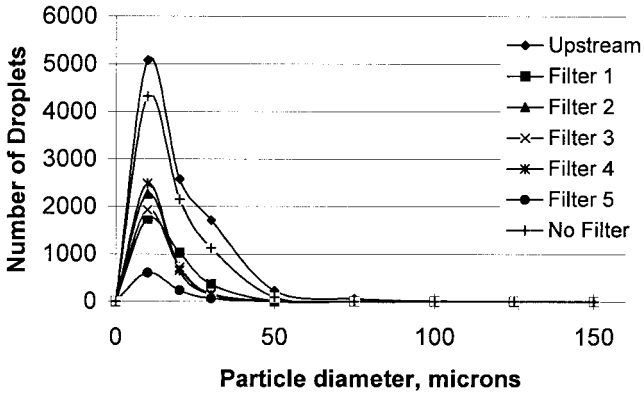


**Figure 5. Particle-size distribution of water droplets upstream and downstream of the five filters listed in Table 2.**

The comparison of the upstream and no filter curves show that a small fraction (about 10%) of the water droplets are separated by the settler without the filter medium in the line. With the filter medium present, the separation is significantly enhanced.

$$A = \left(\frac{4}{d_f \rho}\right) \times w \tag{10}$$

where $\rho$ and $w$ are density of the fiber and mass of the fiber in the filter sample.

### *Effect of wettability*

Coalescence performance is known to depend on other factors such as wettability (Vogler, 1998). Table 5 summaries the surface tension of the test fluid $\gamma_{LV}$. Table 6 summarizes the wettability of deionized water on the four materials that make up the fibers, as well as the separation efficiencies. Figure 7 has photographs of the drops of water on the glass and polymer surfaces. Contact angles are used to characterize the wettability, with an angle 0° for complete wettability and an angle of 180° no wettability. The glass fibers have the highest wettability of all of the materials tested.

The plot in Figure 5 shows that only droplets smaller than about 50 microns were detected downstream of the settler. Comparison of the "Upstream" and "No Filter" curves shows that most of the droplets pass through the apparatus and through the settling tank when no filter is present in the filter

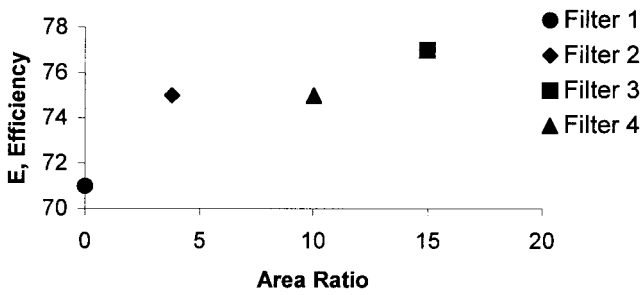


**Figure 6. Effect of nanofibers on filter performance.**

The data are plotted as the efficiency vs. the area ratio of nanofiber surface area to glass fiber surface area for the four filters of the same thickness.

**Table 5. Physical Property of Liquids in the Coalescence Experiments**

| Type of Fluid | Viscor 1487 | Deionized Water |
|---|---|---|
| Specific gravity | 0.832 | 1 |
| Surface tension (at 28°C), dynes/cm | 28.5 | 71.0 |

sample holder. However, when filter samples are in the sample holder the data curves show a significant decrease in the number of droplets detected in the stream exiting the settling tank.

Comparison of the data between the different filter samples shows the best coalescence performance was obtained by the glass fiber only media. This result is consistent with literature (Voyutskii et al., 1955; Hazlett, 1969a; Moses and Ng, 1985; Basu, 1993) where the optimal performance is reported for high wettability fibers.

Table 2 summarizes the calculated separation efficiencies ($E$) and quality factors ($QF$) obtained for the five filter media as defined by Eqs. 1 and 3. In this particular application, the best separation efficiency ($E$) of the 3 mm thick filter media was obtained with the composite filter of glass fibers plus Polyamide nanofibers as compared to the other filters of the same thickness. The combination of glass fibers and polymer nanofibers did not improve performance when compared through the quality factor ($QF$). The three composite media with nanofibers all had about the same efficiency ($E$) even through the area ratios were significantly different.

### *Effect of filter depth*

The efficiency and quality factor were highest for the 5 mm thick sample, filter 5, compared to the 3 mm samples, showing the effect of filter thickness on the filter performance. The better capture efficiency by filter 5 compared to filter 1 can be explained by the dependence of capture on drop size on the filter depth. Smaller particles are more difficult to capture and require thicker filter for a given capture efficiency.

Using Eq. 5, knowing the single oil phase pressure drop for filter 1, $\Delta P_1 = 0.30$ kPa, and the two-phase pressure drop $\Delta P_2 = 0.53$ kPa and $K_2/K_1 = 1$ (Viraraghavan et al., 1997), $\varepsilon_2$ was calculated to be 0.92. $S$ was determined using Eq. 7 and is found to be nearly the same for both filters. Equation 1 was applied to determine the coalescence efficiency $\eta_c$ for the water-in-oil emulsion and listed in Table 2.

The coalescence efficiency decreases with an increase in depth, as shown by the experimental results on Filters 1 and 5. This conclusion is in agreement with the findings of Mathavan and Viraraghavan (1992) who found that the coalescence efficiency in a peat bed and in a granular organo-clay/anthracite mixture bed decreased with an increase in the depth of the bed.

**Table 6. Contact Angle and Wettability with Water at 28°C, and Filter Separation Efficiency**

| Polymer Solution | Glass | PAN | Polyamide | Nylon |
|---|---|---|---|---|
| Contact angle, $\theta$, degree | 0 | 38.6 | 52.1 | 46.4 |
| Wettability, dynes/cm | 71.0 | 55.4 | 43.6 | 49.0 |
| Separation Efficiency (E), % 3 mm filter | 71 | 75 | 77 | 75 |
| Separation Efficiency (E), % 5 mm filter | 92 | | | |

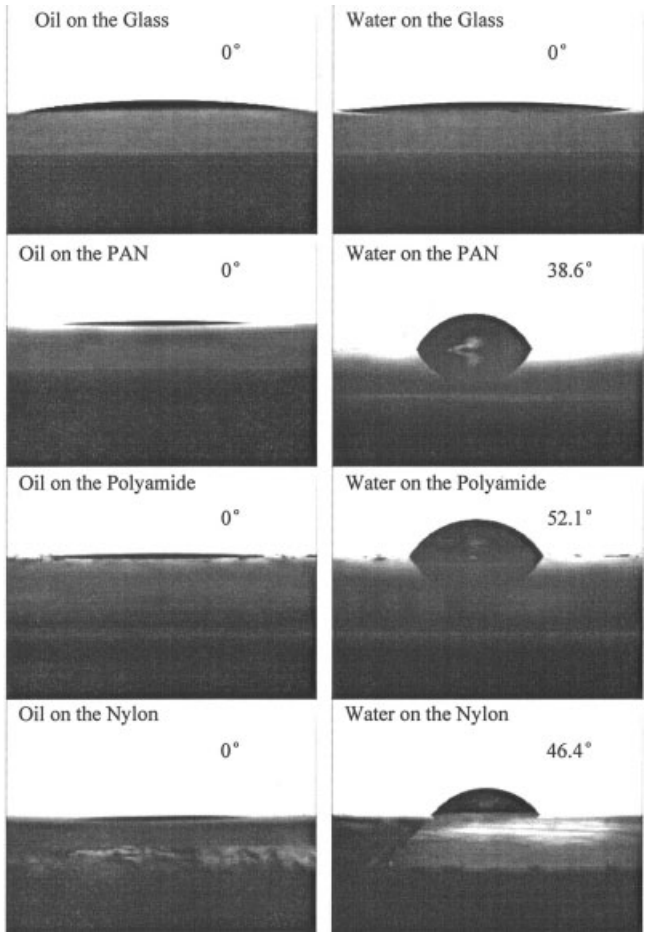


**Figure 7. Oil and water drop on four different surfaces using the drop shape method.**

For the coalescence process to be effective in a coalescer bed, the ratio of water drop diameter to fiber diameter should increase with an increase in filter depth. This trend was not observed in the 3 and 5 mm depth glass fiber filters.

For the experiments conducted here, the steady-state values from the experiments are used to calculate the quality factor, and are listed in Table 2. Because of the design of the experiments, using a settling tank to remove the larger drops and the probability of re-entrainment, the quality factor calculated for this data is not a true representation of the filter performance, but represents the combined system performance.

When compared in terms of the quality factor, the glass fiber media with no polymer nanofibers perform better than the media with nanofibers. This is attributed to two factors: first, the glass fibers have a higher wettability than the polymer nanofibers; hence, the glass fiber media perform better to capture and coalesce to form larger drops, and, second, in the liquid phase filtration the large surface area of nanofibers significantly increases the drag force, causing the pressure drop to increase faster than the capture efficiency. This is the opposite of what can occur in gas phase filtrations where the nanofibers are small enough that the gas flows past the nanofibers in a slip-flow mode (Graham et al., 2002).

Higher wettability polymers may perform better than the polymers used in this work. Also, these results cannot tell us

whether the media with nanofibers would perform better than the media without nanofibers for oil-water mixtures with drops that are submicron in size. Both of these topics are left for future work.

### *Effect of flow rate*

Flow rate plays an important role in the filter media performance. It determines not only whether an emulsion will be generated in the mixing pipe, but also controls the migration behavior of the dispersed droplets. High flow rates cause a larger pressure drop across the filter media (Figure 8). High flow rates (230 mL/min) produce a smaller mean size of water droplets in upstream, as shown in Figure 9. Figure 9 also shows the water particle-size distribution downstream of Filter 1 and settler for the 100 and 230 mL/min flow rates. The separation efficiency for the experiment with flow rate of 230 mL/min is 54% compared to 71% for a flow rate of 100 mL/min.

## Conclusions

In this work, the various factors such as fiber size, wettability, filter depth, and flow rate are evaluated for their effect on coalescence efficiency. Composite filters of glass fibers and polymer nanofibers showed improved separation efficiency over glass fiber media. Surface area varies with the diameters of the fibers and the amount of polymer electrospun into the filter media. The experimental data show us that even small additions of nanofibers increase in the capture efficiency of the filter media, but also cause an increase in the pressure drop. In general, the higher wetting fibers provide better coalescence. In this work the combination of glass fibers and polymer nanofibers did not improve performance when compared through the quality factor. The overall coalescence efficiency decreased with an increase in depth for the experimental conditions applied here. The flow rate has a significant effect on performance, with lower flow rates performing better than higher flow rates. As expected, thicker filters provide better coalescence but with higher-pressure drops.

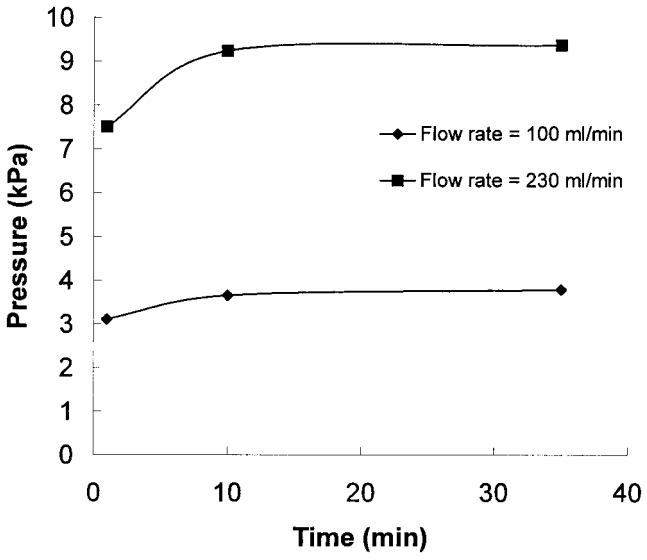


**Figure 8. Pressure drop vs. time for different flow rate for Filter 1.**

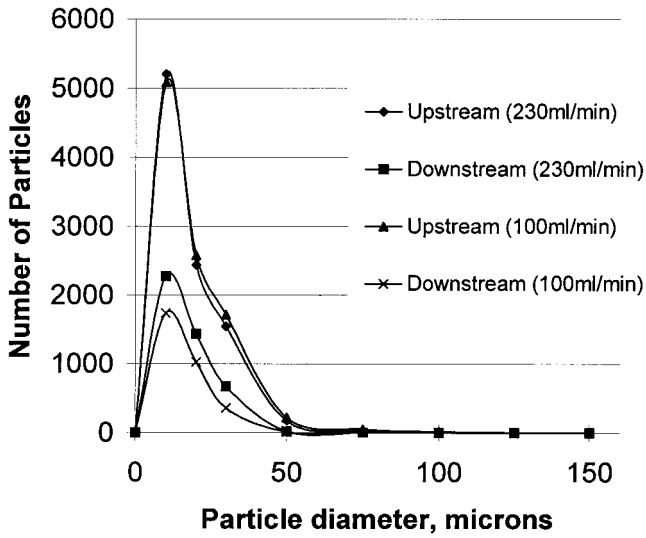


**Figure 9. Particle-size distribution (number of particles per unit volume) of water droplets upstream and downstream of Filter 1.**


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