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Keywords: hydrophobic/oleophilic fabric mem- brane, oil spill cleanup, oil collection well design, theoretical model.

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ABSTRACT

Hydrophobic/oleophilic polyester fabric membranes prepared by a simple waterborne polymeric nanoparticle coating process were used to build up oil collection wells for the oil spill over water surface. In order that mass flux and separation time can be predicted, a simulation of oil flow through the wall of collection well in a simple and small apparatus was made. The developed model along with the experimental data analysis was shown to enable the characterization of membrane performance by a membrane resistance, R_M, to the Poiseuille flow of a liquid oil driven by gravity. A hydrophobic/oleophilic fabric membrane with a specific R_M value can then be used to accomplish oil spill cleanup and recovery with predictable separation time. The agreement between theoretical and experimental results confirmed the validity of the developed theoretical model. Moreover, the derived equations predict adequately the performance of oil collection wells and show insight into the design of large-scale oil spill cleanup systems in the potential applications. Finally two oil collection well designs, for example, were demonstrated for the in situ cleanup and recovery of spill oil over water surface of a standard swimming pool with different well allocation, size, and separation time.

Keywords: hydrophobic/oleophilic fabric membrane, oil spill cleanup, oil collection well design, theoretical model.

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I. INTRODUCTION

Oil spills resulting from oil production, transportation, and storage pose serious environmental pollution and consequent ecological problems [1-7]. Some common methods including oil skimming, oil-absorption materials, in situ burning, chemical dispersion, and oil consuming microbes have ever been deployed to clean oil spills [6-9]. These technologies, however, have various limitations. Oil skimmers are expensive and inefficient; oil-absorption materials suffer from inadequate absorption capacity, low selectivity, and poor recyclability and result in secondary pollution; in situ burning creates toxic fumes; chemical dispersants are expensive and often toxic, and the dispersed oil resulting from this method can settle and pollute the ocean floor; oil-consuming microbes also pose problems in large numbers, as they can reduce subsea oxygen levels, thereby threatening marine life and the delicate balance of the surrounding ecosystem. Therefore, the development of new oil-water separation methods with high efficiency, low cost and improved safety has been the focus of extensive research in this field.

Several recent articles have been devoted to the review of researches on the separation of oil-water mixtures using membranes with special wettability [10-24]. Separation membranes with hydrophobicity and oleophilicity surely served as the preferred candidates for the purpose of oil spill cleanup. Deng et al. [25] developed a hydrophobic and oleophilic mesh that separates oil from water continuously in situ, providing a means of recovering spilt oil from surface waters. They also proposed the mass flux model when the separated liquid through the membrane was driven by capillary. However, they did not consider the influence of gravitational force and inertia. Song et al. [26] demonstrated a small-scale oil collection prototype device consisting of a superhydrophobic and superoleophilic stainless steel mesh mounted in a leak-proof manner on the open end of a glass beaker that can be held in place at a variable angle with respect to the horizontal. The hydrophobic/oleophilic mesh attracted the floating oil, simultaneously separating it from water and collecting it in the beaker. The oil mass flux, however, could only be measured experimentally. A bench-scale oil collection apparatus was built up by Xue et al. [27]. It is a cylindrical container with a solid wall in the lower half part and a superhydrophobic/superoleophilic textile wrapped on the mesh wall in the upper part. Oil would be selectively filtered into the cylinder through the wrapped textile by immersing the cylinder into the stratified oil-water mixture. Their work showed large-scale and practical application for consecutive collection of oil from water. Wang et al. [28] utilized a mini boat fabricated from their superhydrophobic fabric for self-driven oil spill cleanup. The cloth boat can automatically recycle crude oil spills while floating freely on water, demonstrating great potential in environmental remediation. A hydrophobic/superoleophilic nanofibrous container was designed for the purpose of collecting oil spills by Qiu et al. [29]. Their device could continuously collect various kinds of oils from the surface of water. Su et al. [30] designed a simple oil–water separation device with lidless box shape by using the superhydrophobic textile and stainless steel mesh for oil spill accidents. Due to superhydrophobicity of the textile, water was impeded while oil automatically penetrated the mini "boat" through the textile. After enough oil was collected in the mini boat, a pumping system was utilized to transfer oil into a container.

As mentioned above, some prototype devices utilizing hydrophobic/oleophilic separation membranes have been proposed for oil spill cleanup and collection. Nevertheless, these studies were lack of fully quantitative delineation of the oil-water separation process. Therefore, it is much desirable that a theoretical model can be developed for the predictions of mass flux and separation time by using typical collection well with hydrophobic/oleophilic separation membranes in the cases of oil spill accident. Large-scale and practical application for consecutive collection of oil spill from water can then be made good progress.

Figure 1 shows a possible scenario of oil spill over large area of water surface. Oil collection wells are deployed and positioned regularly over the water surface for the in situ cleanup and recovery of the spilt oil. By using a hydrophobic/oleophilic fabric separation membrane, water will be retained outside the cylindrical separation membrane due to its hydrophobicity and oil will permeate through the separation membrane under the influence of gravity due to its oleophilicity. As more and more oil is collected in the well, it can be pumped out to a container.

The objective of this work is to design oil collection wells, as shown in *Figure 1*, for oil spill over water surface with predictable mass flux and separation time by using hydrophobic/oleophilic polyester fabric membranes. A simulation of oil flow through the wall of collection well in a simple and small apparatus was made first. The developed theoretical model along with the experimental data analysis thereafter enable the characterization of membrane performance by a membrane resistance, R_M, to the Poiseuille flow of a liquid oil driven by gravity. A fabric membrane with a specific R_M value can then be used to accomplish oil spill cleanup with predictable separation time. Derived equations, which can predict adequately the performance of oil collection wells and may show insight into the design of large-scale oil spill cleanup systems in the practical applications, is expected.

II. MODELING

The bench-scale oil collection apparatus is shown in Figure 2. Figure 2 (a) shows the cylindrical well with a glass wall in the lower half part and a hydrophobic/oleophilic fabric wrapped on the top of glass wall in the upper part. Oil would be selectively penetrated into the cylinder through the wrapped fabric by immersing the cylinder into the stratified oil-water mixture in a beaker as shown in *Figure 2 (b)*. With the passing of the oil, a bulk flow in the oil layer around the cylinder toward the fabric was created. *Figure 2 (c)* shows schematically the bulk flow in the oil layer around the cylinder toward the fabric during oil-water separation process. Variation of oil surface level with time can then be monitored.

The mass flux of a liquid through the membrane subjected to a pressure drop can be represented by the Hagen-Poiseuille equation [31-33], in honor of the two men credited with its original derivation:

$$J = \frac{\varepsilon \pi r_p^2 \Delta P}{8 \mu L} = \frac{\Delta P}{\mu R_M} \qquad (1)$$

where the flux J is described as a function of the effective porosity ε, the pore radius r_p, the pressure drop ΔP, the liquid viscosity μ, and the total distance traveled by the liquid passing through the membrane L. The membrane resistance, R_M, to the Poiseuille flow of a liquid is therefore defined by

$$R_M \equiv \frac{8L}{\varepsilon \pi r_p^2} \qquad (2)$$

It is noteworthy that L, ε, and r_p of the fabric membranes, as shown latter in Figure 3 by the SEM micrographs, cannot be exactly described. In this work, they are lumped into R_M for membrane characterization even if they are unknown to us. However, a simple and small apparatus using the fabric membrane along with the data analysis on the oil liquid height as function of time (see latter in the Experimental and Results and Discussion sessions) can then be used to overcome the dilemma and evaluate the value of R_M. Because R_M is advocated as a characteristic property of the fabric membrane itself, R_M is supposed to be independent of liquid oil properties such as density and viscosity.

Considering the condition as shown in Figure 2 (c), the volume balance for the element ΔH in a time interval Δ*t* is

$$\bar{J} \times A \times \Delta t = \Delta V \qquad (3)$$

where $\bar{J}$ is the average flux through the membrane area A, and can be evaluated by the following equation:

$$\bar{J} = \frac{\int_0^H J\,dH}{\int_0^H dH} \qquad (4)$$

Applying Equation (1) for J with ΔP = ρ*gH*, where ρ is the liquid density and g is the gravitational acceleration, in the case of gravity-driven liquid flow and rearranging, Equation (4) becomes

$$\bar{J} = \frac{\int_0^H \left(\frac{\rho g H}{\mu R_M}\right) dH}{H} = \frac{\left(\frac{\rho g H^2}{2 \mu R_M}\right)}{H} = \frac{\rho g H}{2 \mu R_M} \qquad (5)$$

Therefore, Equation (3) may be written

$$\left(\frac{\rho g H}{2 \mu R_M}\right)(\pi D H)\Delta t = \frac{\pi}{4}\left(d^2 - D^2\right)(-\Delta H) \qquad (6)$$

In the limit as ΔH and Δt approach zero, we have

$$\frac{dt}{dH} = \frac{-\left(d^2 - D^2\right)\mu R_M}{2 D \rho g H^2} \qquad (7)$$

A solution for the time required to lower the height of oil level from H_o to a specified H can be obtained by solving Equation (7) subject to the initial condition, H (0) = H_o :

$$t(H) = \left[\frac{\mu R_M\left(d^2 - D^2\right)}{2 D \rho g}\right]\left(\frac{1}{H} - \frac{1}{H_0}\right) \qquad (8)$$

According to Equation (8), a straight line should be obtained when the time required for lowering the liquid height from H_o to H is plotted against 1/H. Note that the slope of the straight line is a value of that in brackets from which the membrane resistance, R_M, may be calculated. The experimental data of t versus 1/H, therefore, enable the R_M value of a specific membrane to be easily determined. It should be noted that the time required to completely evacuate the oil over water surface will be infinitely long because Equation (8) has a singularity at H= 0

Another form of the solution of Equation (7) is :

$$H(t) = \frac{\mu R_M\left(d^2 - D^2\right) H_0}{\mu R_M\left(d^2 - D^2\right) + 2 D \rho g H_0 t} \qquad (9)$$

The oil level falling rate can then be determined by Equation (10)

$$-\frac{dH(t)}{dt} = \frac{\left[\mu R_M\left(d^2-D^2\right)\right](2D\rho g)H_0^{\ 2}}{\left[\mu R_M\left(d^2-D^2\right)+2D\rho g H_0 t\right]^2} \tag{10}$$

It should be noted that a similar simulation can be made on the oil collection well unit, which is shown in Figure 1. By substituting W^2 for $\left(\pi d^2/4\right)$, Equation (8) becomes

$$t(H) = \left[\frac{2\mu R_M\left(W^2-\frac{\pi}{4}D^2\right)}{\pi D\rho g}\right]\left(\frac{1}{H}-\frac{1}{H_0}\right) \tag{11}$$

As depicted by Equation (11), the separation time needed for lowering oil level from H_0 to H of an oil with viscosity μ and density ρ by using a hydrophobic/oleophilic fabric well membrane with diameter D and resistance R_M over a water domain of W square can be evaluated. Oil spill cleanup systems can be built up through scaling up of the oil collection well units.

III. EXPERIMENTAL

Materials and methods that used for the preparations of hydrophobic/oleophilic fabric separation membranes are given. The methods that used for the characterization and performance assessment of the fabricated oil-water separation membranes are given as well. At the same time, the separation time as a function of oil residue for a model oil collection well unit using the specific hydrophobic/ oleophilic separation membrane can be experimentally monitored.

3.1 Materials

Aqueous polytetrafluoroethylene dispersion solution (PTFE DISP 30, 60 wt%, 220 nm) was purchased from Multichem Trading Co., Ltd. Polyester fabric (100%, twill weave, 165 g/m², 495 μm) with warp/weft density (inch⁻¹) of 710/47 was purchased from local fabric store. Toluene and hexadecane both with purity of 99% were purchased from Mallinckrodt Chemicals and Alfa Aesar, respectively. Oil-soluble dye Sudan Black B and water-soluble dye Rhodamine B were purchased from Sigma-Aldrich. All experiments were conducted using ultrapure water with a resistivity of 18.2 MΩ˙cm (Milli-Q plus purification system, Millipore, USA).

3.2. Fabrication of polymeric nanoparticle-coated fabric membranes

The original PTFE dispersion solution (60 wt%) was diluted with water by volumetric ratios of 2:1 and 1:1, respectively, to obtain the 40 wt% and 30 wt% dipping solutions. The polyester fabric substrate was rinsed with ethanol and water in sequence and then dried at 50 °C prior to coating. Fabric substrate was then immersed into PTFE DISP dipping solution for 5 minutes. After dripping the redundant solution, the coated fabric was dried and cured in an oven at 150 °C for 2 hrs. For the preparation of fabric oil collection well wall, polyester fabric was first wrapped on a glass vial and hot melted by using a soldering iron. The cylindrical polyester fabric substrate with a diameter of 2.8 cm was removed from the vial and thereafter rinsed, dried, coated and cured as mentioned above for the flat polyester substrate. The fabric oil collection well wall was then mounted on the top of the vial, tied with Teflon seal tape, and clamped as shown in Figure 2 (a).

3.3. Characterization of polymeric nanop-article-coated fabric membranes

The static contact angle (SCA) was measured with 5 μL liquid droplet by using a contact angle analyzer (FTA 1000B, First Ten Angstroms) with charge-coupled device (CCD, GC655, Allied). All measurements were repeated four times for data statistics and reproducibility. Actually, this was presented by the values of mean and standard deviation of the four data. Morphologies of coated surfaces were examined with a scanning electron microscope (SEM, Hitachi SU8010, Japan) at operating voltage of 10 kV. For the purpose of visualization, a gold film of about 10 nm in thickness was deposited on the solid surface.

3.4. Evaluation of Fabric Membrane Resistance, R_M

For the evaluation of fabric membrane resistance, the oil collection well consisting of hydrophobic/oleophilic separation membrane at the upper part was immersed into the stratified oil-water mixture of 80 ml oil and 200 ml water in a beaker with diameter of 7.0 cm as shown in

Figure 2 (b). Toluene with surface tension of 27.73 mN/m, density of 0.86 g/cm^3, and viscosity of 0.56 cP at 25℃ and hexadecane with surface tension of 27.10 mN/m, density of 0.77 g/cm^3, and viscosity of 2.3 cP at 25℃ were used as the oil liquids in this work. Oil was dyed black with Sudan Black B for the purpose of enhancing the visual effect. The variation of oil level height with time as oil penetrated through the fabric separation membrane was recorded for the evaluation of R_M. All measurements were repeated three times for data statistics and reproducibility.

It should be noted that once R_M is determined, Equation (11) can be used to delineate the separation time as a function of oil residue for a model oil collection well unit using the specific hydrophobic/oleophilic separation membrane.

IV. RESULTS AND DISCUSSION

SEM micrographs with low magnification (50X) and high magnification (1000X) in top view of the pristine fabric, fabrics once-coated with PTFE DISP of concentrations 30, 40, and 60 wt%, respectively, were shown in Figure 3. As shown in Figure 3 (Aa) and 3 (Ba), the pristine PET fabric was composed of smooth microfibers winded into a regular woven structure. After PTFE nanoparticle coating, the generation of nanoscale roughness on individual fibers can be seen in Figures 3 (Bb-d). Micro/nanoscale hierarchical rough structure on separation membrane surface was created and the formation of more hydrophobic surfaces is expected. As shown in Figure 4, water contact angles on the as-coated polyester fabric surfaces were increased from 132.1° to 143.3° as the concentrations of dipping solution were increased from 0 to 60wt%. On the other hand, all the as-prepared fabrics were easily wetted by toluene and hexadecane. Data of repeated contact angle measurements with high agreement were shown in Table 1. The wettability of the separation membranes with texture structure and micro/nanoscale hierarchical roughness was shown to be well characterized by contact angle. Hydrophobic and oleophilic fabric membranes for possible oil/water separation were successfully fabricated.

The bench-scale oil collection apparatus using PET fabric once-coated with PTFE DISP 30 wt% was shown in Figure 5. Continuous oil collection *in situ* from a water surface proceeded while the collected oil was pumped out the well through a tube. The variation of oil height outside the well with time was recorded for the evaluation of R_M. Table 2 shows the height of both toluene and hexadecane level as functions of time for the once-coated fabric separation membrane with PTFE DISP concentration of 30, 40 and 60 wt%, respectively. According to Equation (8), the mean values of separation time were plotted against 1/H as shown in Figure 6. Straight lines were obtained and the slope of the straight line is a value of that in brackets from which the membrane resistance, R_M, can then be calculated. As shown in Table 3, coefficients of determination (R^2) higher than 0.9981 were resulted from the analyses of three membranes and two different oils. This indicated that the experimental results are well correlated by the model. Allowing for uncertainties in the measurements and calculations, the same R_M values were determined for the same membranes by using two oils with different density and viscosity. The advocate that R_M should be a characteristic property of the fabric membrane itself is evidenced.

Table 3 also shows the effect of dipping solution concentration on the R_M value of the as-prepared membranes. Higher membrane resistance may be resulted from more concentrated dipping solution. This is due to possible decrease in porosity and pore size of the membranes. It is noteworthy that the values of membrane resistance determined in this work are highly consistent with those determined previously by using a different apparatus along with the data analysis for characterizing performance of the as-prepared fabric separation membranes [34]. With the as-determined membrane resistance $R_{M,}$ separation time needed for an oil residue to be achieved by a hydrophobic/oleophilic fabric can then be theoretically predicted by Equation (8). Figure 7 shows the comparison between experimental and theoretical oil level (H) as functions of time by using oil collection wells with R_M values determined previously as shown in

Table 3. Excellent agreement between them can be found. The profound accuracy of predictions for the two different oil liquids also indicates that the estimation of mass flux and separation time of other Newtonian oil liquids through hydrophobic/ oleophilic membranes by this approach is looking quite promising.

The experimental data shown in Table 2 and Figure 7 may also be presented as the relationship between separation time and initial height of oil level. The time required to lower the height of oil level from H_o to a specified H is depicted by Equation (8). As shown in Figure 8, Equation (8) predicts well the relationship between them. It is interesting to note that the extra time required to evacuate split oil from initial height (H_o) to a specific final height (H) of 0.2 cm becomes less and less as H_o is increased. This result can be verified by examining Equation (8) for the effect of H_o on separation time. When H_o is increasing, the second term in parentheses of Equation (8) is decreasing and finally becomes negligible. Therefore it doesn't take much more time to evacuate oil spill with much higher level. This is due to larger gravitational driving force and penetrating membrane surface area available in the cases of higher initial height H_o. Figures 9 (a) and (b) show the predictions of oil level height (H) and oil level falling rate (-dH/dt) as functions of H_o by using Equations (9) and (10), respectively. It is obvious that the variations of both height and height falling rate of oil with time are much more significant in the early stage of oil-water separation process. By examining Equation (10), the initial oil level falling rate is proportional to the square of H_o. For a specific oil residue to be achieved, the separation process is more efficient for oil spill with higher level. This manifestation of the oil collection well design is important in the applications.

The validation of model was evidenced by the experimental results as mentioned above. Therefore, it is plausible to design the collection well for oil spill over water surface by using hydrophobic/oleophilic fabric separation membrane following the developed model. The application of the proposed collection wells was exemplified by the oil spill over water surface of a standard swimming pool. As shown in Figure 10 (a), 10 oil collection wells with diameter of 1 m are regularly allocated on water surface such that the ratio of oil collection well unit dimension to well diameter (W/D) is ten. Wells fabricated from hydrophobic/ oleophilic fabric separation membrane with membrane resistance (R_M) of 84 cm^{-1} are used to recover toluene of 2 cm thick over water surface. The question to be answered is: how long will it take to recover toluene at a residue percentage (H/H_o x 100%) of 10%? As calculated by using Equation (11), about 17800 L toluene is collected in 21.91 hr. In another allocation as shown in Figure 10 (b), 40 oil collection wells with diameter of 2 m and W/D = 2.5 can speed up the collection of about 15700 L toluene in 2.04 hr at the same residue percentage of 10%. Performance evaluation of the hydrophobic/oleophilic oil collection wells, therefore, becomes possible by following the protocol.

V. CONCLUSIONS

In summary, a theoretical model was developed for the design of oil collection wells to clean up and recover oil spill over water surface by using hydrophobic/oleophilic polyester separation membranes. The developed model along with the experimental data analysis was shown to enable the characterization of membrane performance by a membrane resistance, R_M, to the Poiseuille flow of a liquid oil driven by gravity. A hydrophobic/oleophilic fabric membrane with a specific R_M value can then be used to accomplish oil spill cleanup and recovery with predictable separation time. The agreement between theoretical and experimental results confirmed the validity of the developed theoretical model. Moreover, the derived equations predict adequately the performance of oil collection wells and show insight into the design of large-scale oil spill cleanup systems in the practical applications. Finally two oil collection well designs, for example, were demonstrated for the in situ cleanup and recovery of spill oil over water surface of a standard swimming pool with different well allocation, size, and separation time.

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Funding and/or Conflicts of interests/Competing interests

The authors declare that they have no conflict of interest.

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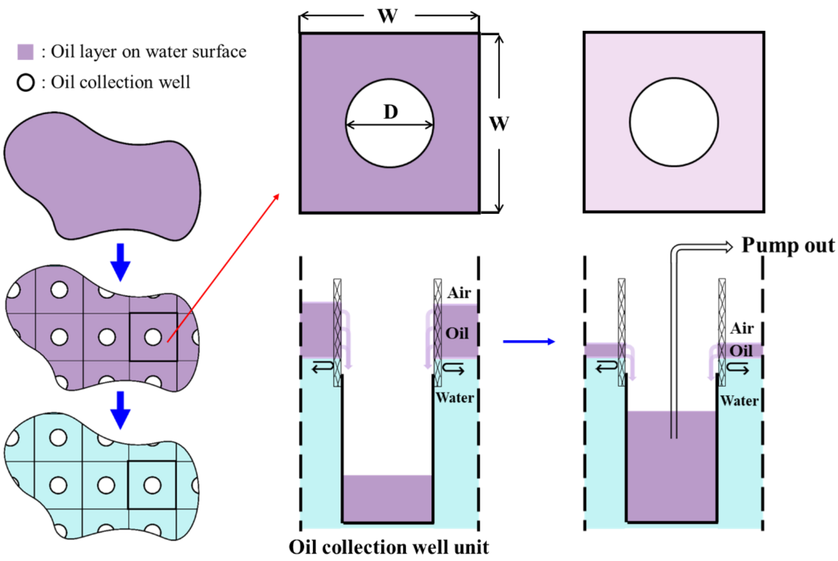

Figure 1: Cleanup and recovery of oil over water surface as demonstrated by an oil collection well unit using a hydrophobic/oleophilic fabric separation membrane

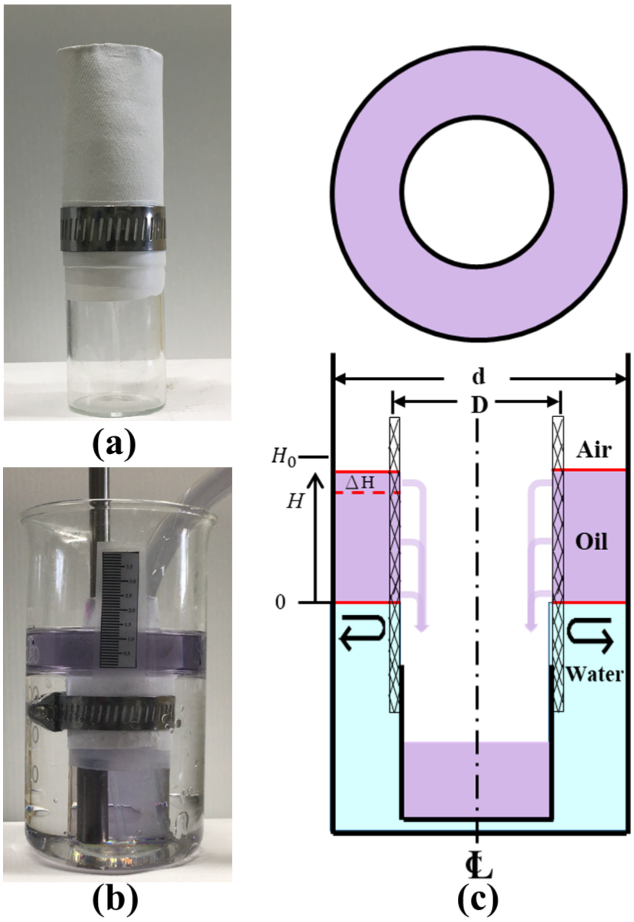

Figure 2: (a) Photograph of the oil collection well utilizing a hydrophobic/oleophilic fabric separation membrane. (b) Photograph of the oil collection apparatus for the stratified oil-water mixture in a beaker. (c) Schematic diagram of the apparatus showing the bulk flow in the oil layer around the cylinder toward the fabric during oil-water separation process. D =2.8 cm, d = 7.0 cm.

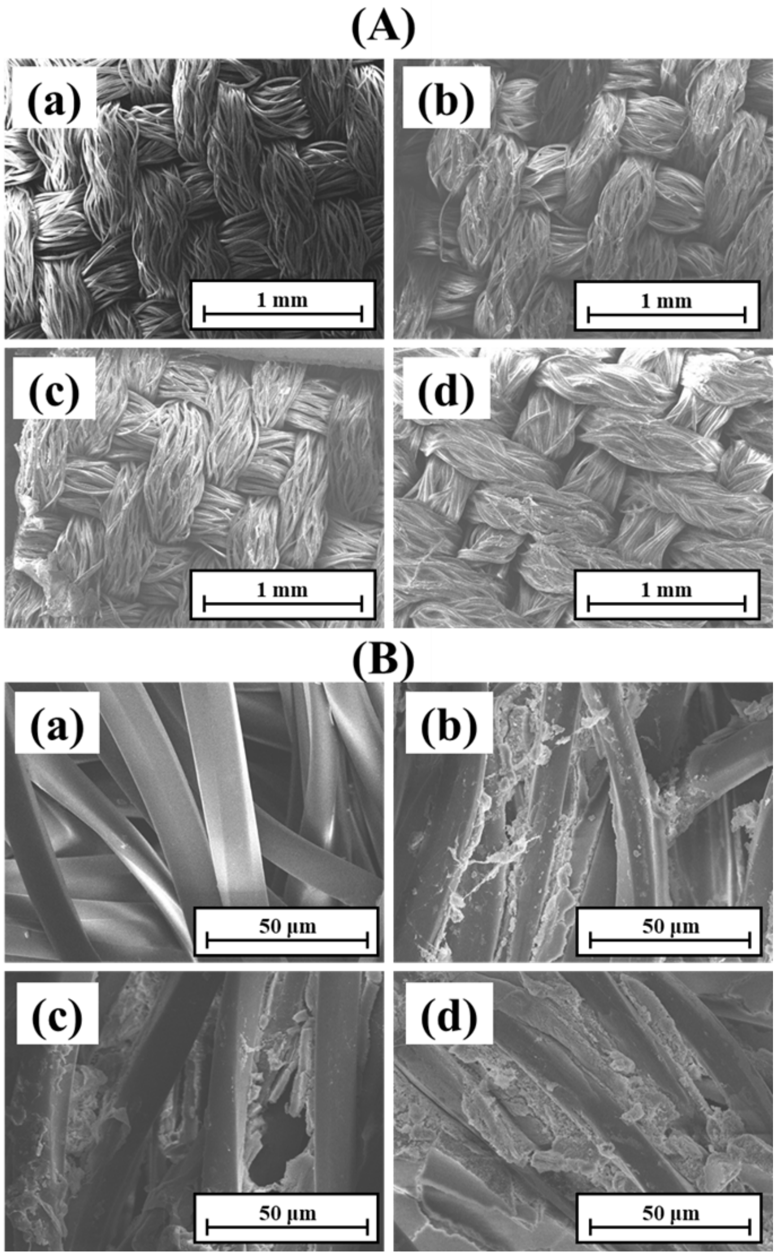

Figure 3: SEM micrographs of fabrics coated with PTFE DISP of concentrations (a) 0 wt%, pristine, (b) 30 wt%, (c) 40 wt%, and (d) 60 wt%. Magnification: (A) x50, (B) x 1000

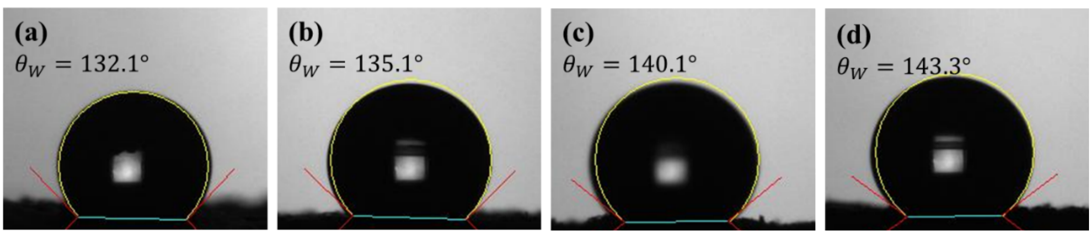

Figure 4: Water contact angles of fabrics coated with PTFE DISP of concentrations (a) 0 wt% (pristine), (b) 30 wt%, (c) 40 wt%, and (d) 60 wt%.

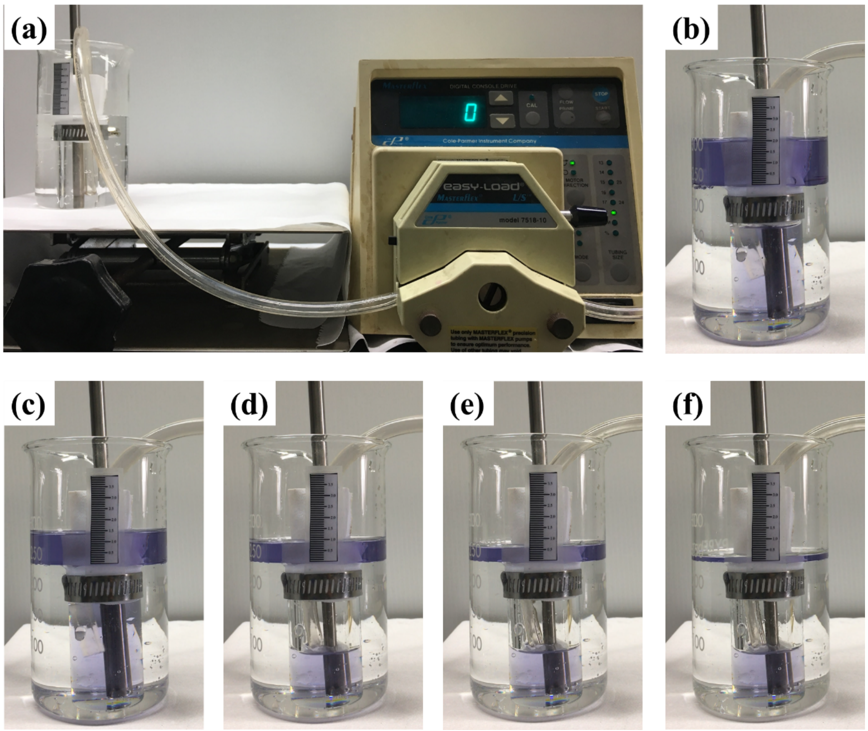

Figure 5: (a) Photographs of the experimental apparatus with coated fabrics with PTFE DISP 30 wt% for continuous oil collection *in situ* from a water surface. (b-f) Toluene (dyed black)-water separation temporal stages at (b) 0 s, (c) 10 s, (d) 30 s, (e) 50 s, and (f) 180 s. The collected oil was pumped out the well through a tube.

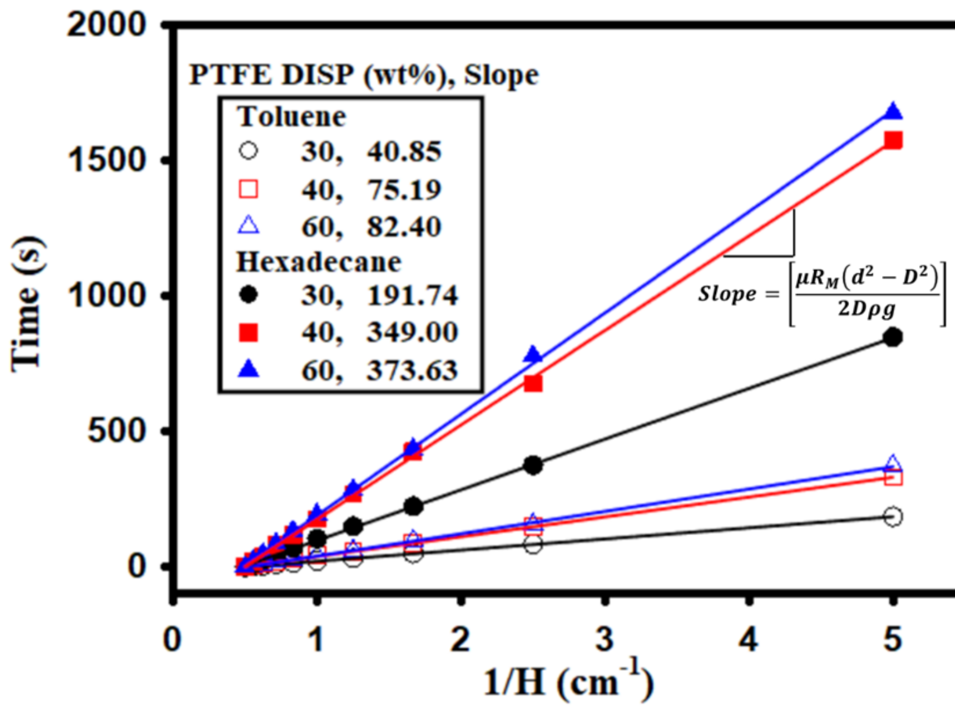

Figure 6: Separation time as functions of inverse of oil height by using hydrophobic/oleophilic fabrics coated with PTFE DISP concentrations of 30, 40, and 60 wt%, respectively, for toluene and hexadecane. H_o = 2.0 cm.

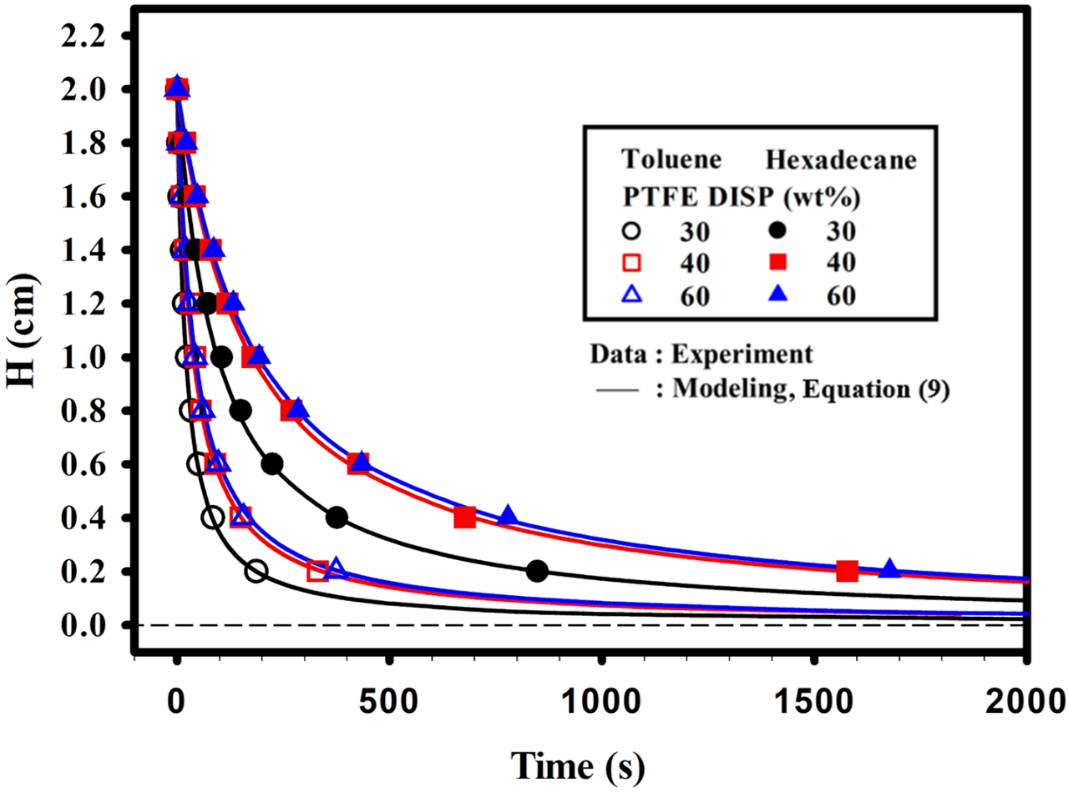

Figure 7: Comparison between experimental and theoretical oil level (H) as functions of time by using hydrophobic/oleophilic fabric membranes coated with PTFE DISP concentrations of 30, 40, and 60 wt%, respectively, for toluene and hexadecane.

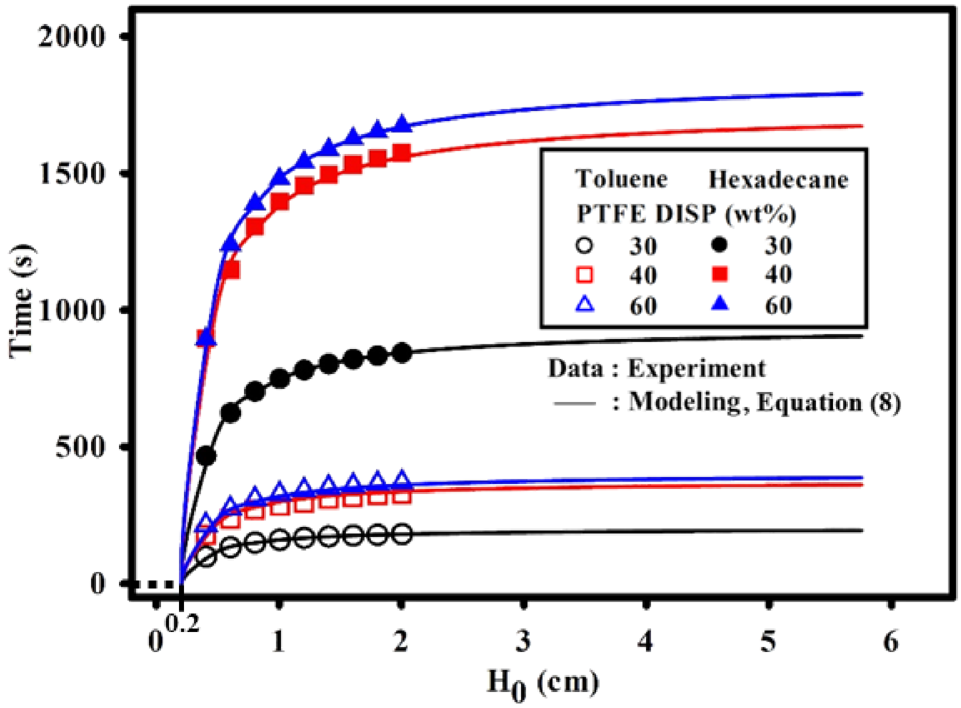

Figure 8: Comparison between experimental and theoretical separation time as functions of initial oil level (H_o) by using hydrophobic/oleophilic fabric membranes coated with PTFE DISP concentrations of 30, 40, and 60 wt%, respectively, for toluene and hexadecane.

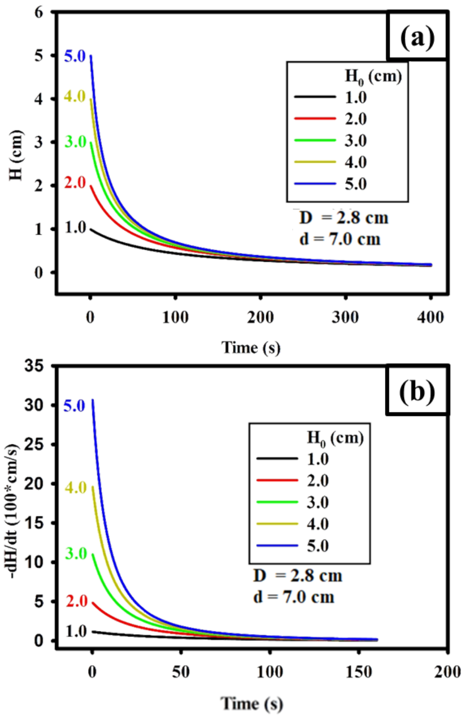

Figure 9: Parametric study of separating toluene with an oil collection well by using hydrophobic/oleophilic fabrics coated with PTFE DISP concentrations of 30 wt%. (a) The H as a function of time. (b) The oil level falling rate as a function of time.

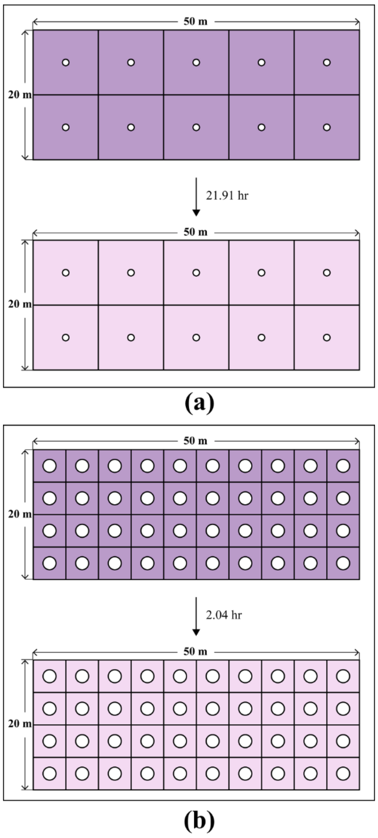

Figure 10: Two proposed in situ oil collection well designs with R_M = 84 cm^{-1} for 2 cm thick toluene over water surface of a standard swimming pool of 20 x 50 m^2 to achieve oil residue percentage = 10%. **(a)** D = 1 m, W/D = 10, 10 oil collection wells, ~17800 L toluene removed. **(b)** D = 2 m, W/D = 2.5, 40 oil collection wells, ~15700 L toluene removed.

Table 1: Static contact angles of the pristine and fabrics coated with various PTFE DISP concentrations

PTFE DISP (wt%)	Pristine	30	40	60
Static contact angle (°) Mean ± SD (n = 4)				
Water	131.1 ± 0.5	135.7 ± 1.6	139.9 ± 0.7	142.7 ± 0.9
Toluene	N/A			
Hexadecane	N/A			

Table 2: Height of oil level as functions of time for the coated fabric separation membrane with PTFE DISP concentration of 30, 40 and 60 wt%. H_o = 2.0 cm.

PTFE DISP (wt%)	30	40	60
Test oil	Toluene		
	Hexadecane		
H (cm)	Time (s) Mean ± SD (n = 3)		
2.0	0	0	0
	0	0	0
1.8	2.28 ± 0.17	3.93 ± 0.14	4.96 ± 0.32
	11.77 ± 0.04	18.91 ± 0.86	21.37 ± 0.65
1.6	5.13 ± 0.02	9.92 ± 0.29	11.41 ± 0.31
	26.66 ± 0.12	41.60 ± 1.31	47.23 ± 0.86
1.4	11.23 ± 0.15	17.64 ±0.39	18.79 ± 0.35
	45.44 ± 0.12	79.08 ± 5.03	85.67 ± 2.05
1.2	16.15 ± 0.60	31.86 ± 1.24	28.39 ± 0.55
	71.74 ± 0.18	118.87 ± 4.08	132.02 ± 1.93
1.0	23.04 ± 0.53	43.26 ± 1.01	41.88 ± 0.57
	104.10 ± 0.37	176.89 ± 4.08	193.00 ± 1.45
0.8	32.68 ± 0.59	55.91 ± 1.23	60.38 ±0.56
	149.03 ± 1.51	268.75 ± 12.81	284.6 ± 1.44
0.6	50.04 ± 0.29	89.14 ± 0.85	96.81 ± 0.91
	223.21 ± 4.83	425.98 ± 6.24	434.13 ± 5.13
0.4	83.68 ± 0.53	149.51 ± 2.41	156.38 ±1.64
	375.36 ± 9.10	677.02 ± 3.73	777.88 ± 1.27
0.2	185.61 ± 5.53	330.67 ± 7.85	374.00 ± 4.97
	846.82 ± 13.48	1577.05 ± 6.32	1676.33 ± 12.47

Table 3: Evaluation of R_M for fabrics coated with PTFE DISP concentrations of 30, 40, and 60 wt%.

PTFE DISP (wt%)	30	40	60
Test oil	Toluene		
	Hexadecane		
R^2	0.9997	0.9993	0.9993
	0.9995	0.9981	0.9996
$\frac{\mu R_M(d^2 - D^2)}{2D\rho g}$	40.74	75.19	82.40
	189.00	331.85	373.63
R_M (cm^{-1})	83	153	168
	84	155	166