EFFECT OF SURFACE WETTABILITY ON LIQUID-LIQUID COALESCENCE FILTRATION

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ABSTRACT

Water-in-oil emulsion separations are important to petrochemical industries. Water droplets of less than 100μm diameter are present as secondary emulsions. The presence of water reduces the efficiency of the fuel combustion, the water droplets can plug small orifices, and water can dissolve polar compounds from the fuel and form corrosive materials that can damage engine parts. Thus, fuel filtration extends the life of engine. Coalescence filters are efficient and effectual for the removal of secondary emulsions. The surface functionalization of fibers used to make coalescence filters can potentially provide cleaner fuel with reduced water concentration.

The aim of this work is to evaluate the effectiveness of coatings on fibers in filter media to remove water molecules from secondary emulsions. The fiber surface wettability is a crucial factor in coalescence phenomena. The approach of this work is to study effect of surface wettability on coalescence filtration by varying surface wetting characteristics of fibers with the use of surface modifying silane coupling agents. The coupling agents used in this work are 3-aminopropyltriethoxysilane (APTS), (2-(carboxymethylthio) ethyltriethylsilane) (CES), and ((heptadecafluoro-1,1,2,2-tetra-hydrodecyl) trichlorosilane) (FTS).

This work includes preparation of depth filter media with specified coatings where the fibers were coated prior to forming the media, or the media were constructed and the coating was applied to the performed media. The difference in wettability of the filters was quantified using the modified Washburn's equation. Filters were tested in a liquid-liquid coalescence experiment. The filter media with APTS functionalized surface having an intermediate wettability was found most effective for water-in-oil coalescence filtration. Recommendations for future work are proposed.

Keywords: silanes, coatings, wettability, coalescence, filtration

INTRODUCTION

The problem of separating two immiscible liquids (e.g. water-oil) when one is finely dispersed within other is frequently encountered in chemical engineering applications. Some of the industrial examples include liquid-liquid extractions, dewatering and removal of water that exists as haze in aviation fuel [1].

Today, water contamination in refinery fuels can be a bigger problem than solid contaminations. Water in fuel can corrode and plug engine parts and is a significant contributor to tank bottom corrosion and bacterial growth. In addition, water may contain corrosive materials like chlorides that will cause equipment damage. Unfortunately, it does not take much water to cause a problem. Water along with surfactants which lower interfacial tension, at low concentrations (100 ppm) can cause a product to be off-specification due to haze or color [2].

Water exists as a primary or secondary emulsion in fuels. Primary emulsions are water drops greater than 100μm in diameter can be removed by using gravity settling. Secondary emulsions, i.e. droplets size less than 100μm in diameter are difficult to remove as the stokes settling velocity is low and separation is aided by Brownian motion and shear – induced coalescence to produce drops large enough to settle out.

There are several techniques available to increase drop size like alternating electrical fields, addition of chemical coagulants and coalescence by flow through porous solids. Amongst the pretreatments to water in oil emulsions, coalescence is attractive since it has a higher effectiveness of separation under favorable conditions. Smaller droplets are coalesced into larger drops and they are eliminated by subsequent gravity settling.

COALESCENCE FILTRATION

Coalescence filtration enhances the removal of smaller drops by enlarging the drops to sizes that are easier to remove by other methods (such as settling). The main steps involved in coalescence filtration using fibrous filter media are capture of droplets on fibers, coalescence of droplets into larger drops, and migration of the enlarged drops out of the medium.

The performance of filter media is usually characterized by pressure drop across the filter media and the separation efficiency (in conjunction with a settling tank). The separation efficiency is dependent on the properties of the dispersion (e.g. composition, density, viscosity, droplet diameter) and on the fiber bed properties (e.g. material, fiber geometry, surface structure, porosity) [3]**.** In liquid-liquid coalescence filtration, along with the fluid velocity and other parameters, the fiber surface wettability has a significant effect on the capture, coalescence and drainage of the drops.

INFLUENCE OF WETTABILITY OF FIBERS ON FILTER PERFORMANCE

The effect of the chemical nature of the solid surface on coalescence media is normally considered as either low -surface energy or high-surface energy materials. It is known that the ratio of the critical surface tension of a solid to the liquid surface tension determines the character of solid wettability [4].

An intermediate wettability gives the most effective separation, thus for the best performance the filter should be sufficiently water-wetted to coalescence the water, but not so saturated as to produce excessive pressure drop by the accumulated water. It has been found that the fiber contact surface area is more important than pore size. The water droplets in water-in-oil emulsions must displace the oil film from the wet fiber for the attachment to be effective. A water droplet easily displaces oil on hydrophilic surfaces. The displacement of the continuous phase by the discontinuous phase on a low energy surface, such as polyethylene or PTFE (polytetrafluoroethylene, i.e., Teflon®), should be considerably less than on a high energy surface, such as glass. The wetting behaviors of the water-in-oil or oil-in-water emulsions are considered to be important in determining the performance of the coalescence efficiency.

OBJECTIVE

Efficiency of coalescer filter media made of glass fibers is influenced by the surface property of the glass fibers. This property is related to the wettability of the surface. Silane coupling agents can alter the surface energy of silica and glass.

The objective of this work was to study the effect of silanes on the wettability of the glass fibers in filter media and their performance in liquid- liquid coalescence filtration experiments. Coupling agents (silanes) were selected and coating techniques were developed. To quantify the wettability of the fibrous media the modified Washburn's equation was used; the penetration weight of liquid into the filter is directly related to the advancing contact angles of the liquid penetrating the filter media.

SILANES AS COUPLING AGENTS

Organofunctional silanes may be used as adhesion promoters between organic polymers and mineral substrates. They can function as a surface modifier or primer or an adhesive based on the quantity at the interface. As a surface modifier they form a mono or multimolecular layers on many materials without affecting the mechanical properties of the underneath substrate.

The coupling mechanism of the organofunctional silanes depends on a stable link between the organofunctional group (**Y**) and hydrolyzable groups (**X)** in compounds of the structure X_3SiRY. The organofunctional groups provide the reactivity with the polymer; the hydrolyzable groups are intermediates that form the silanol groups for bonding the mineral surfaces [5].

The advantages of choosing silanes to alter the wettability of the surface are: (1) the covalent bond between the organosilane molecule and the glass is relatively stable, (2) the amount of organosilane coating may be varied by duration time of treatment to provide a means of achieving different degrees of wettability, and (3) different functional organic groups of different silanes can impart different wetting properties [6].

The common hydrolysable groups (X) of organosilanes are chloro, acyloxy and amino. The byproduct of hydrolysis of chlorosilanes is hydrohalic acid. Acyloxy and amino substituted silanes are far more susceptible to

hydrolysis in the presence of water; these products do not give acid on hydrolysis. Also they are more convenient to use.

SURFACE FUNCTIONALIZATION OF FIBERS:

Silane coating can be done by solution based deposition and by vapor phase deposition. The glass fibers are coated with solution based deposition and are then used to make filter media. Filter made from uncoated fibers are subsequently coated with vapor phase deposition. Both these techniques are described below.

Solution Deposition

The glass fibers were cleaned by immersion in a mixture of 70/30 by volume of sulfuric acid and hydrogen peroxide (technical grade) for at least 30 minutes, followed by rinsing with distilled water, dried under a stream of N_2 gas and are considered as "cleaned" glass. The pre-treated hydrophilic glass fibers were oxidized by UV ozone for 10 minutes.

Organosilanes were deposited onto the cleaned and oxidized glass fibers using a solution deposition method. Glass fibers were placed in a solution of 3mM of organosilane in hexane (HPLC grade). The chemisorption of organosilanes was allowed to occur for 45 minutes to 1 hour. Finally, the glass fibers were removed from organosilane solution, rinsed with hexane, and dried under a stream of N_2 gas.

Vapor Phase Deposition

Uncoated glass fiber filters that were to be coated were cleaned under a stream of N_2 gas. They were then suspended for 30 minutes in a desiccator above a glass dish that contained a mixture of silane solution in paraffin oil (3gm) with 200 microliter of silane.

Contact Angle Measurement

Contact angles are a measure of wettability of glass surfaces. Solution deposition was used to coat flat glass surfaces (glass slides), which we assume to have the same wettability of glass fibers used to make filter media. This measurement was made using a Goniometer (Rame-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 [8]. Table 1, gives the values of contact angles of silanes selected.

Estimation of surface energy using contact angles

A measure of surface energy of the surface to be wetted by the liquid is given by the angle of contact. The surface energy of the substrate/ air, γ_s was estimated by using contact angles of two different liquids water (liquid 1) and methylene iodide (liquid 2) and the Girifalco- Good- Fowkes- Young [13] equation:

$$\gamma_1 (1+\cos\theta) = 2 (\gamma_s^D \gamma_1^D)^{0.5} + 2 (\gamma_s^p \gamma_1^p)^{0.5}$$

$$\gamma_2 (1+\cos\theta) = 2 (\gamma_s^D \gamma_2^D)^{0.5} + 2 (\gamma_s^p \gamma_2^p)^{0.5}$$

where γ_1 and γ_2 are surface tension values of liquids 1 & 2, γ^p is the polar component and γ^D is the dispersion component of a substance.

The dispersion component (γ^D) denotes effective surface tension due to the dispersion or general van der Waals interactions. The polar components (γ^p) denote the effective surface tension due to polar components [13]. The values of γ_s^p and γ_s^D for water and methylene iodide could be obtained from literature [14]. The above equations can be solved using contact angle values from Table 1 to obtain values of γ_s^D and γ_s^p, giving a value of surface energy $\gamma_s = \gamma_s^D + \gamma_s^p$. The γ_s of different surfaces calculated using the abovementioned equations is given in Table 2.

The untreated glass surface has the highest surface energy which can be explained by the least contact angle made by the water on a hydrophilic surface forming a thin film. The APTS treated surface which has an intermediate contact angle for water has the highest surface energy compared to other two silanes. The higher the surface energy, the greater the liquid wets the surface.

Table 1: Contact Angles of Flat surfaces

SILANE	Contact angle θ for water	Contact angle θ for methylene iodide
APTS (3-aminopropyltriethoxysilane)	39°	38°
CES (2-(carboxymethylthioethyltrimethyl silane)	62°	57°
FTS ((heptadecafluoro-1,1,2,2-tetra-hydrodecyl) trichlorosilane)	104°	84°

Table 2.Calculated surface free energy of silane coated glass surfaces

Glass Substrate with silane coating	Surface free energy, γ_s, (mJ/m^2)
Untreated Glass	74.4
APTS (3-aminopropyltriethoxysilane)	65
CES(2-(carboxymethyl-thioethyltrimethylsilane)	42
FTS ((heptadecafluoro-1,1,2,2-tetra-hydrodecyl) tricholorosilane	13.5

Silane Depletion Study:

This study was conducted with the aim of studying the deterioration of silane-treated glass fibers that are immersed in water for a period of 2 hours in the slurry to make filter samples.

Glass slides were prepared using the aforementioned procedure for solution deposition technique with FTS (3mM solution in hexane). Liquids used for this test were: Water, Water + Acrylic Binder, Water with a pH 2.75 using sulfuric acid and finally all the three as per the recipe of slurry to make the filter media. Table 3, gives the change in values of the contact angles. All values are averages of three measurements taken on three slides for each liquid. Changes in the contact angles were insignificant in all of the solutions indicating that the 2 hour exposure to the liquid solutions when forming the filters has negligible effect on the silane coatings.

Table 3: Contact Angle using silane and testing with different liquids

Sample Description	Before exposure to liquids	After 2 Hrs of exposure
No Liquid	76.63°	77.71°
Water	73.23°	73.26°
Water + Sulphuric Acid	77.90°	74.86°
Water + Carboset- 560	73.26°	72.37°
Water + Sulphuric Acid+ Carboset- 560	74.95°	74.51°

WETTING STATICS AND DYNAMICS

The aim of this research work is to determine the effect of surface wettability of filter media on coalescence performance for filtration of water in oil emulsion. The direct approach of characterizing the wettability of a solid material surface using contact angle cannot be used for filter media. Instead, the liquid penetration approach is used to measure the contact angles of filter media treating the pores as a bundle of uniform capillaries. This method of the liquid penetration is based on the equilibrium capillary pressure and Washburn's equation.

Washburn's equation is based on the capillary driving force of a liquid that penetrates a compact vertical bed of particles with small pores and viscous drag:

$$h^2 = \frac{r_{eff} \cos\theta_a \gamma_{lv} t}{2\eta} \qquad (1)$$

where η is viscosity of the penetration liquid , γ_{lv} is the surface tension of the penetrating liquid , r_{eff} is the effective capillary radius , *h* is the height of penetrating liquid in the bed in time t, and θ_a is the advancing particle contact angle measured through the liquid phase [9].

In filter media, r_{eff} is very difficult to determine precisely and thus leads to significant errors in the penetrating rates of liquid. To overcome shortcomings and errors prone to visual penetration rate, liquid weight gain measurements are used instead.

The weight, *w*, is related to the height in the capillary by

$$w = \varepsilon.\rho.\pi.R^2 h \qquad (2)$$

where ε is the porosity of the packed filter column, ρ is the density of the liquid, and *R* is the inner radius of the capillary.

Finally when we combine equations 1 & 2 by, we get

$$w^2 = r_{eff}\,\varepsilon^2(\pi R^2)\frac{\rho^2\gamma_{lv}\cos\theta_a t}{2\eta} \qquad (3)$$

Or

$$w^2 = \frac{c\rho^2\gamma_{lv}\cos\theta_a t}{\eta} \qquad (4)$$

To determine the value of $c=r_{eff}\varepsilon^2(\pi R^2)^2/2$, a total wetting liquid must be used for which the contact angle is assumed to be zero. From the measurement of slope $\Delta w^2/\Delta t$ and knowing liquid characteristics the value of c can be computed.

Once the contact angle is found for a total wetting liquid, it can be used for another liquid from the slope of the curve.

$$S = c\rho^2\gamma_{lv}\cos\theta_o \Big/ \eta \qquad (5)$$

where *S* is the measurement of the curve slope $\Delta w^2/\Delta t$ [10].

A concept called the Lipophilic / Hydrophilic Ratio (*L/H*) [11] is used in this work. In this approach, the contact angles of an apolar liquid (representative of oil phase) and a polar liquid (representative of water phase) for a filter medium are tested. The *L/H* ratio is related to the contact angles by

$$\frac{L}{H} = \frac{\cos\theta_o}{\cos\theta_w} \qquad (6)$$

Using Eq.(5) to eliminate $\cos\theta_0$ from the equation we get

$$\frac{L}{H} = \frac{S_o\eta_{o.}c_w\rho_w{}^2\gamma_w}{S_w\eta_w.c_o\rho_o{}^2\gamma_o} \qquad (7)$$

Both c_w and c_o are the same for a filter medium, thus *L/H* value reflects the wettability of the filter medium. *L/H* values when less than 1 indicates the surface is hydrophilic and values greater than 1 indicate the surface is lipophilic, *L/H* equal to 1 means equal wettability.

EXPERIMENTAL WORK

PREPARATION OF FILTER SAMPLES

The filter samples were made of glass fibers supplied by Hollingsworth and Vose with no further treatment. 0.5 gm of glass fibers were dispersed in a dilute aqueous solution of sulfuric acid (pH 2.5-2.75) and 0.5 ml of acrylic binder solution (Carboset 560, BF Goodrich). The slurry was stirred for 2 to 3 hours.

The slurry was vacuum filtered onto a fine mesh screen in a mold with five holes with an inside diameter of 2.54 cm to form five filter samples. The applied vacuum pressure was from 100 to 160 kPa [12]. The filter samples were then dried and heated in an oven for 2 hours at 120^0C.

EXPERIMENTAL SET UP FOR WETTABILITY STUDY

The experimental setup for this work is illustrated in Figure 1. Filters made from the above procedure were characterized prior to wettability studies. Filter samples were weighed using a microbalance; thickness was

measured using Vernier Caliper. The thickness was maintained uniform throughout the experiment. Filters were tested for their porosity using a Pycnometer.

In Figure 1, a glass tube was suspended from a wooden beam that was attached to a scissors stand which could be raised and lowered using a knob. The glass tube has a tapered diameter which was the same as that of the filter. The filter medium under test was cleaned using nitrogen gas and then placed inside the tapered end of the tube.

A glass beaker with reference liquid, with temperature maintained around 23^0-25^0C was placed on the plate of an electronic balance. A stop watch was placed in front of the electronic balance along with a video camera facing both balance and stop watch. The cylinder descended slowly with a low speed of 1.0 mm/sec it was carefully done with several manual practices in order to get reproducible results. It was done with the extremity of the tube just touching the reference liquids. The video camera and stop watch were turned on when the filter medium touched the reference liquid to record the change in weight with time. The decline of the glass tube was ended and the liquid rose through the filter until it reached the top of the medium, causing an increase in weight of the cylinder. The video recording was stopped when liquid reached top of the filter medium.

The increase in weight of the cylinder was equal to the decrease in weight of the reference liquid placed on the balance. The evaporation rate of the liquids was measured and accounted for in decrease in weight of reference liquids. The experimental data were obtained from the video camera for every 5 seconds until the liquid reached top of filter [16].

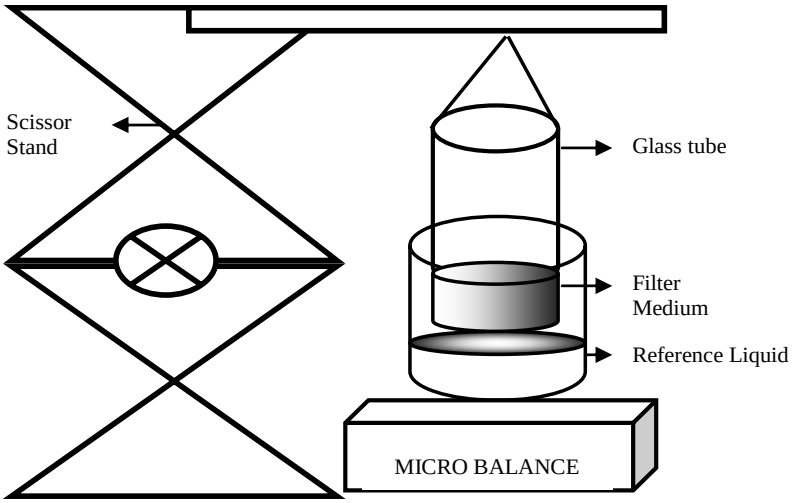

Figure 1: Schematic representation of experimental set up for measuring filter media wettability.

Materials and Methods

B -Glass fibers obtained from Hollingsworth and Vose were made into filters using the procedure described above. These filters were coated with silane using was a solution 0.4 to 0.8 % (vol/vol) silane in water sprayed with 2 nozzles at the fibers. Filter samples made with a vapor deposition of CES, FTS and APTS on glass based filter media were tested.

The oil used for both filtration and wettability test is a calibration fluid, Viscor oil 1487. This oil has properties similar to that of diesel fuel and gasoline. As stated by the manufacturer they have specifically controlled specific gravity and viscosity, higher and safer flash points as well as lower hydrocarbon content. The Viscor oil 1487 that was used met requirements of SAE J-967 and ISO 4113 specifications. Physical properties of water and Viscor Oil 1487 are presented in Table 4. Surface Tension was measured using a tensiometer at 25^0C.

Table 4: Characteristics of reference liquids at 25^0C

Reference Liquid	γ (N/m)	ρ (Kg/m^3)	η
Viscor Oil 1487	0.0285	832	2.49(ASTM)D 445
Water	0.072	998	0.001($Ns.m^2$)

Table 5: Filter Sample Physical Characteristics (All values are averaged over three samples)

Filter Sample	Technique	Reference Liquid	Mass (g)	Height (mm)	Porosity
Glass	Uncoated	Water	0.5444	9.474	0.914
Glass	Uncoated	Viscor Oil 1487	0.5397	10.414	0.917
APTS	SD	Water	0.4006	9.525	0.892
APTS	SD	Viscor Oil 1487	0.4488	9.448	0.85
APTS	VPD	Water	0.4332	9.443	0.93
APTS	VPD	Viscor Oil 1487	0.4107	9.886	0.936
FTS	VPD	Water	0.421	10.212	0.924
FTS	VPD	Viscor Oil 1487	0.4132	9.93	0.91
CES	VPD	Water	0.4671	9.556	0.942
CES	VPD	Viscor Oil 1487	0.4237	9.446	0.932

SD: Solution Deposition
VPD: Vapor Phase Deposition

LIQUID-LIQUID COALESCENCE FILTRATION EXPERIMENT

A mixture of water-in-oil was used in the experiments, in which deionized water was dispersed in oil. The oil used for the tests was VISCOR 1487. The schematic of experimental set-up used shown in figure 2. The oil was pumped through the system using a peristaltic pump (2) (Master flex, model L/S EW-07543-60) at a flow rate of 150 ml/min to 175ml/min. At the mixing pipe (3) water droplets were introduced to make the water-in-oil emulsion using a syringe pump (WPI, Model sp101i) at a flow rate of 60 μl/min(4). The droplet concentration was measured at sampling point (1) to obtain the inlet concentration at interval of 10 minutes. Filter media were placed in the filter holder (5) and the water in oil emulsion was pumped through it. Smaller droplets coalesce into larger drops. The pressure drop over the filter was measured as a function of time. A gravity settling tank (6) was used to remove the enlarged drops. The smaller drops are carried into the reservoir tank (7). The concentration of the flow going into the reservoir tank was measured at sampling point (2). Sampling at points (1) and (2) was carried out to achieve particle size distribution using particle size analyzer (Particle Sizing systems, Model 780 Accusizer, sensor for 0.5μ to 500μ).

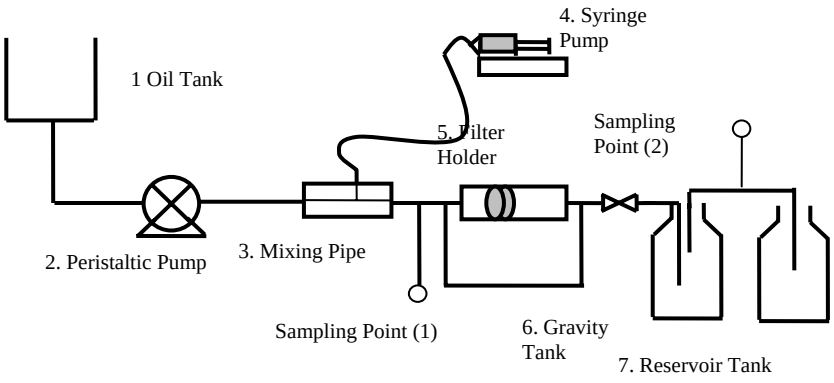

Figure 2: Schematic of Liquid-liquid Coalescence experiment Set-up

RESULTS AND DISCUTION

Surface wettability has a considerable influence on the performance of coalescing filters. Intermediate wettability is reported to give best results. The results about the effect of silane coats on fibers and also the best technique to coat fibers are reported previously [17]. The silane depletion study indicated negligible change in the contact angle values after the treated fibers were submerged in the slurry to make filters. Some of the wetting kinetics results are illustrated in Figures 3- 6.

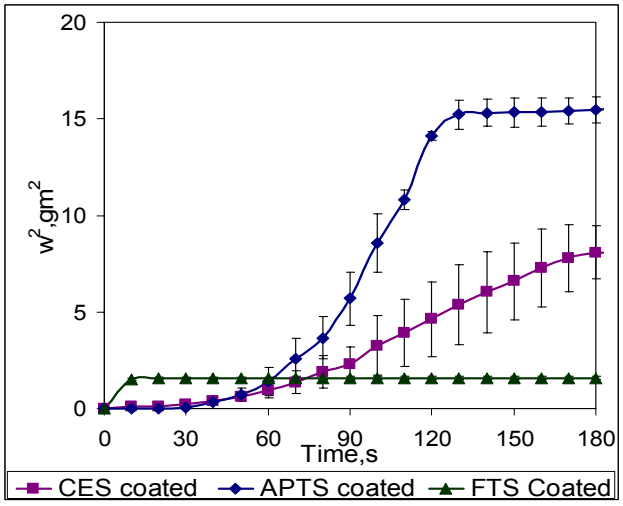

Figure 3: Wetting kinetics for different filter media with water as reference liquid

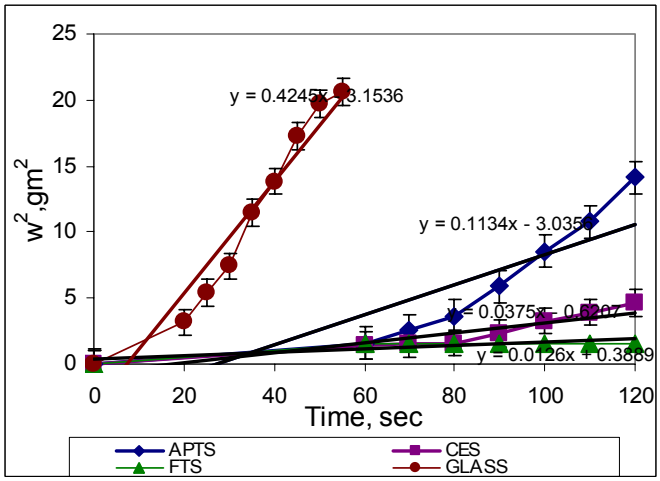

Figure 4: Initial slope of filter media using water as reference liquid

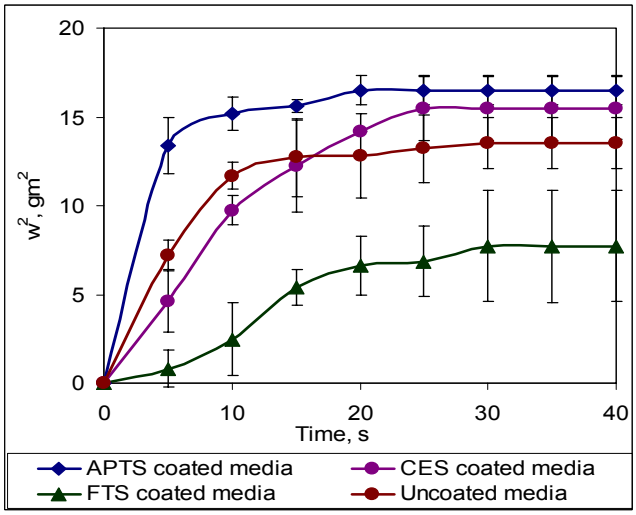

Figure 5: Wetting Kinetics Using Viscor Oil 1487 As A Reference Liquid

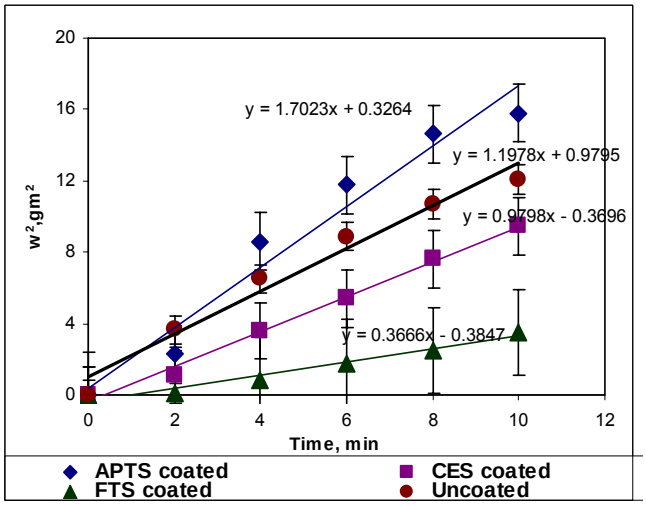

Figure 6: Initial slope of filter media using Viscor oil 1487.

From Figures 4 and 6 we obtain values of slopes for $\Delta w^2 / \Delta t$, which were incorporated into equation 7 to obtain values for wettability of the filter media. The difference in values of L/H indicates the wettability of the media for both oil and water are shown in Table 6. These results are in agreement with Shin [8], FTS based silanes contain the CF_3 group which makes the media a low surface energy material and thus it should not even uptake

any liquid. The high value of L/H for FTS is due to the high contact angle made by water on a glass surface treated with it making it a hydrophobic surface.

CES and APTS silanes have a higher surface energy but not as high as untreated glass, it has been found that, if the *L/H* values are lower than that of FTS, indicating lower values of contact angle by water.

An estimation of the contact angle made by the surface functionalized filter media for water was done using the wetting kinetics data. It is based on the assumption that untreated glass based filter media is completely wet by water with zero contact angle. This assumption was used to estimate the contact angle using Modified Washburn's equation. The contact angles of water obtained using modified Washburn's equation for vapor deposited silanes are shown in Table 7.

Table 6: L/H ratios for Vapor deposited Silanes.

Filter	$\frac{S_o}{S_w}$	$\frac{L}{H}$
Untreated glass fiber	1.86	13.39
APTS coated glass fibers	15.01	108.10
CES coated glass fibers	26.13	188.18
FTS coated glass fibers	29.10	209.57

Table 7: Contact Angles for Vapor deposited Silanes.

Filter	Contact Angle of water on flat glass surfaces	Contact Angle of water using Modified Washburn's Equation
Untreated glass fiber	0^0	0^0
APTS coated glass fibers	41^0	69^0
CES coated glass fibers	62^0	79^0
FTS coated glass fibers	104^0	88^0

LIQUID-LIQUID COALESCENCE RESULTS

The performance of silane coated filters has been tested in liquid-liquid coalescence filtration. These coated filter media were compared with uncoated media. The average properties of the filter media test samples tested in coalescence filtration are summarized in Table 8. The experiments were carried out to investigate the effect of surface energy of fibrous bed composed of different fibers without binder. The average properties of those beds are summarized in Table 9.

The permeability is measured using Frazier Air Permeability tester (Frazier Precision Instrument Co). For fibrous filters, the fluid permeability is given by Darcy's Law

$$\frac{Q}{A} = \frac{k}{\mu}\frac{\Delta P}{L} \qquad (8)$$

Table 8: Measured glass fiber filter media properties (each value is an average of three filters).

Coating	Weight (gm) (±0.04)	Thickness (mm) (±0.03)	Porosity (±0.01)	Permeability $*10^{12}$ (m^2)(±0.11)	%Satu-ration
GLASS	0.458	8.8	0.92	8.4	65
APTS	0.477	8.5	0.91	7.5	47
FTS	0.456	9.0	0.91	8.1	46
CES	0.445	9.5	0.93	7.5	48

Table 9: Measured fibrous bed properties (each value is average of three test samples).

Fiber type/ Coating	Fiber dia. (μm) (± 0.5)	Weight (gm) (±0.05)	Thickness (mm) (±0.04)	Porosity (±0.01)	Permeability *10^{12} (m^2) (±0.12)
Glass /Uncoated	2	0.4327	10.4	0.92	7.5
Glass /APTS	3	0.3178	9.4	0.93	6.3
Polypropylene/ Uncoated	1.5	0.4726	10.5	0.90	0.83

It was observed that as the water-in-oil emulsion passed through the filter, a saturation profile builds up and the pressure drop rose to a steady value as shown in Figure 7. Shin [12] has presented that smaller the diameter of the fiber larger the pressure drop and higher the separation efficiency in liquid-liquid coalescence filter performance.

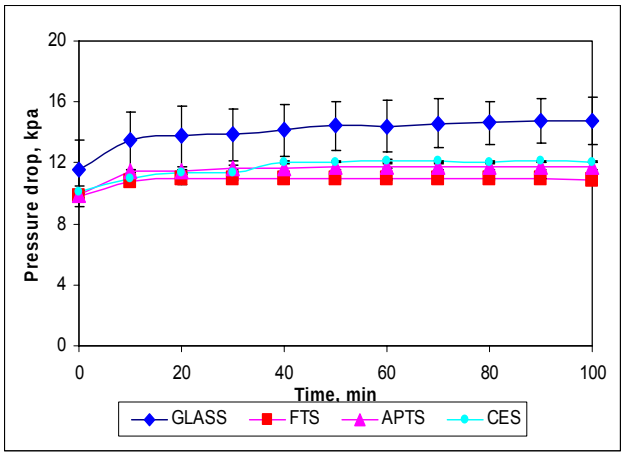

Figure 7: Pressure drop vs. time for the filter media with different coatings. (Each value is an average of the measurements of three filter experiments. The error bars sign standard deviation)

Table 10: Efficiencies and quality factors of filter media with binder

FILTER	**Efficiency, E (±Standard Deviation)**	**Quality Factor, QF (±Standard Deviation)**
UNTREATED GLASS	0.86 (± 0.1)	0.16 (±0.02)
FTS COATED GLASS	0.91 (± 0.06)	0.22 (±0.08)
CES COATED GLASS	0.92 (± 0.02)	0.21 (±0.02)
APTS COATED GLASS	0.96 (± 0.03)	0.30 (±0.05)

The performance of the filter media is evaluated using the separation efficiency, E defined as the mass of water removed divided by the mass of water entering the filter. E is calculated from the experimental data by,

$$E = 1 - \frac{\sum_d \rho N_d \frac{\pi}{6} d_d^3}{\sum_u \rho N_u \frac{\pi}{6} d_u^3} \qquad (9)$$

where N_u is the number of water droplets upstream of size d_u and N_d is the number of water droplets downstream of size d_d.

Quality factor is a measure of the performance of filter media and higher the quality factor better is the performance of the filter media. It is defined as

$$QF = -\ln\left(\frac{C_{out}}{C_{in}}\right) / \Delta P \qquad (10)$$

where C_{out} is the steady state downstream concentration of water, C_{in} is the steady state upstream concentration of water and Δp is the steady state pressure drop across the filter medium. The efficiency and quality factor results for different filter media are summarized in Table 10.

The uncoated glass fiber media with the highest surface energy or (highest wettability) has the lowest separation efficiency and quality factor. These results are in agreement with [12] where water drops formed a thin film around a glass rod instead of attached drops. Similarly, the water is suspected of forming a film around the glass fibers and does not aid further in capture of dispersed droplets.

The CES and FTS based filters have more hydrophobic surface and hence decrease the probability of capture of water drops. The APTS based media has the intermediate surface energy for water and exhibited the highest separation efficiency and quality factor. The glass based filters are highly wetting and hence have the highest saturation producing the highest pressure drop.

With an attempt to elucidate the effect of the surface energy of the fibrous material on the liquid-liquid coalescence experiments were conducted with second set of filters prepared by using different fibers without binder. The figure 8 shows the pressure drop across the fibrous beds and table 11 summarizes the efficiency and quality factor results for fibrous beds.

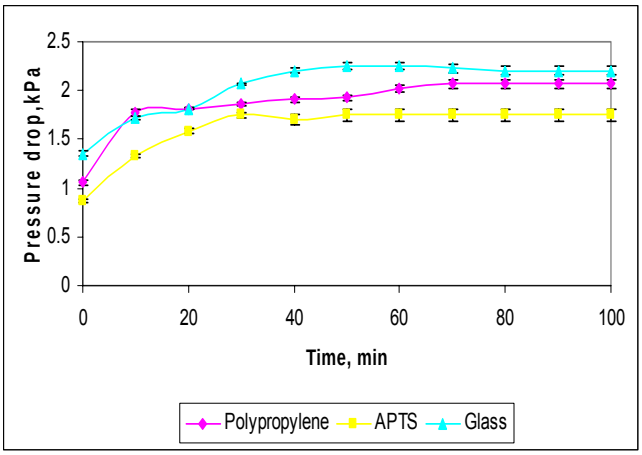

Figure 8: Pressure drop vs. time across the fibrous beds. The error bars show one standard deviation. The data points are the average values of three experiments.

Table 11: Efficiency and quality factors of fibrous beds with no binder

Fibrous bed type	**EFFICIENCY, E (± Standard Deviation)**	**Quality Factor, QF (± Standard Deviation)**
GLASS	0.63 (± 0.03)	0.45 (±0.03)
Glass fibers with APTS coating	0.76 (± 0.05)	0.80 (±0.11)
Polypropylene	0.43 (± 0.1)	0.28 (±0.08)

The pressure drops across the fibrous beds without binder are lower than the pressure drops observed for filter media with binder by a factor of about 5. The polypropylene based fibers showed the lowest separation efficiency and quality factor as the fibers are hydrophobic.

Water droplet displaces oil on a high surface energy material like glass more easily than the low surface energy material like polypropylene [15]. The glass based fibers exhibited higher separation efficiency than polypropylene but with higher pressure drop. The water on a high wetting surface forms a film and for coalescence to occur, the fibers should have an intermediate wettability like the APTS based fibers.

The differences in the separation efficiencies of APTS based filter media with binder (E = 0.96) and APTS based fibrous beds with no binder (E = 0.76) could be due to the differences pore sizes. The pore size was estimated using the optical microscope; APTS filter has average pore size of 0.14 µm and APTS fibrous bed has average pore size of 3.6 µm. The smaller the pores size, higher the coalescer efficiency.

FUTURE WORK

This study can be extended further to other polymeric fibers with a wider range of wettability for water to develop fibrous coalescer beds with improved separation efficiencies. The effect of the presence of binder on wettability and coalescing filter performance needs to be evaluated. The effect of surfactants in liquid-liquid coalescence is an important parameter for fuel filtration. The surfactants are added to improve properties of fuels and may have impact on separation efficiency.

CONCLUSIONS

In this work the modified Washburn equation is used to quantify the relative wettability of a medium. The surface modification using silane coupling agents was achieved and effect of surface wettability on liquid-liquid coalescence filtration has been tested. The liquid-liquid filtration results shows that APTS coated filters with intermediate wettability can achieve highest separation efficiency and quality factor as compare to the CES, FTS and uncoated glass fiber filter media. Experimental results are in agreement that media with intermediate surface energy perform the best.

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