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Evaluation of the Performances of Hydrophobic Woven Meshes versus Liquids having Different Surface Tension in the Fuel-Water Separation Applications

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Abstract: In this study a new methodology has been defined for a deep understanding of the wettability of several woven meshes against liquids having very different wetting behaviour, such as water and jet fuels. At first, we refined the conventional Wilhelmy dynamic contact angle (DCA) technique using several reference solutions having surface tension values between 20–70 mN/m. In this way we covered the range of all the liquids involved in the real world applications. Successively, the study of the woven meshes was completed by the measure of the liquid intrusion pressure (LIP) with the same reference solutions used for DCA measurements.

Correlations between DCA and LIP were finally discussed.

Keywords: Fuel-water separation, Wilhelmy method, liquid intrusion pressure

INTRODUCTION

An ideal fuel filter structure should assure three different functions: separation of solid particles, water coalescence, and water separation (1, 2).

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The first step consists of a pre-filter, generally a non-woven substrate, where the fuel and the water droplets can pass but the solid foreign particles are blocked. These particles may negatively affect the subsequent step, the coalescence process, and therefore should be immediately removed (3, 4).

In the following coalescence stage, two or more droplets of the same liquid, present in an emulsion of two immiscible liquids, join together and, generally, fall down thanks to the different density. As the coalescence is quite a slow process it can be enhanced by the presence of a media which intercepts water droplets and lets them grow. The coalescent media, usually made of coated micro-fibreglass, is able to enlarge the water droplets so that they are big enough to be stopped in the third step (5, 6).

The third stage effectively performs the water separation and is usually composed of a layer of hydrophobic treated synthetic woven mesh. Generally, these fabrics are woven with polyester and polyamide monofilaments with hydrophobic coatings. Among these, silicon based and fluorine based products are common (7, 8). Moreover, performances of the meshes strongly depend on their surface roughness, which can be expressed as the ratio between the true surface area in contact with the liquid and the geometrical area (9, 10). In particular, for hydrophobic coated meshes, the water contact angle increases by increasing the real surface area of the meshes.

The size of the woven meshes is determined in order to be smaller than the water droplets (50–200 μm) to be stopped in the third stage of separation. Moreover, this material should be, ideally, wettable by fuel but un-wettable by water droplets so that the filter media can effectively stop the undesired liquid. In order to use a material for these applications, a full characterization of its hydrophobic performances against liquids with different surface tension is therefore necessary.

EXPERIMENTAL

Materials

A representative of the most popular hydrophobic woven meshes was analyzed. This kind of materials is used for a wide range of applications, like hydrophobic pre-filters for air intakes, venting openings, acoustics devices, oleo-phobic screens and, of course, water/fuel separation.

We analyzed the performances of two families of woven meshes made of polyethylene terefthalate (hereafter PET) and polyamide (Nylon 6,6, hereafter PA) monofilaments. Two numbers after the material acronym indicate the mesh opening and the open area, i.e. respectively the distance between two adjacent threads expressed in μm and the percentage of the area not covered by threads. Wetting properties of untreated materials have been characterized. Moreover, two different hydrophobic coatings are used, in particular silicon based coating for PA and fluorine based coating for PET.

Extended Wilhelmy Method

In the classical Wilhelmy method, a vertically suspended sample is lowered into a liquid (generally water) with a known surface tension (11). The liquid inserts a force on the interface line of the sample. If the liquid is attracted to the sample, it will move up the sample surface. This will create an angle between the liquid surface and the sample of less than 90°. This sample material would be hydrophilic (Fig. 1b).

If the liquid is repelled by the sample it will move down the sample's surface creating an angle between the liquid surface and the sample of more than 90°. This sample material would be hydrophobic (Fig. 1a).

If the liquid will not move along the sample surface, the angle between the liquid surface and sample will be 90°. This sample material will be considered to be neutral (Fig. 1c). Knowing the surface tension of the liquid and the wet length, the contact angle can be determined from measuring the sample's vertical force.

A contact angle value of 90° is generally considered as transition point between wettable and repellent behavior.

The Wilhelmy method provides consistent and accurate results that describe very well the behavior of hydrophobic treated meshes.

However, this method is generally applied using a reference liquid, generally water, of known surface tension. For some applications this procedure is not exhaustive because a substrate could be un-wettable by a certain liquid but wettable by a different liquid with lower surface tension. For example, in the case of water/fuel separation the filter media should be repellent to water and wettable by fuel (8).

For this reason, the hydrophobic behavior of a material should be fully analyzed using a certain number of reference liquids and not only one (water). Those liquids should be chosen with the widest possible range of surface tension.

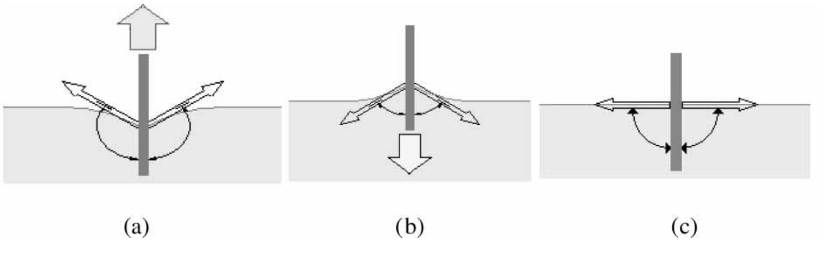

Figure 1. Example of contact angles measurements with the Wilhelmy method: a) $\theta > 90^\circ$, b) $\theta < 90^\circ$, c) $\theta = 90^\circ$.

In this work we defined a number of solutions able to cover the useful range of tensions for water/fuel separation, choosing two liquids (water and acetone), with surface tension values of about 72 and 23 mN/m respectively.

We defined a series of 11 solutions with increasing concentration of acetone in water. Surface tension of each solution was measured using the Du Nouy ring method, with a Kruess K12 tensiometer. Table 1 and Fig. 2 describe the used solutions and the corresponding surface tensions.

It can be noticed that with the chosen solutions we can cover the range suitable for our purpose. With these 11 solutions we measured the dynamic contact angles of different meshes used in water/fuel separation filter for aviation and automotive application. For the measures we used rectangular mesh samples of 35×20 mm dimensions and the immersion length in the liquid was 8 mm.

Water Intrusion Pressure

Another method to describe the hydrophobic performance of technical textile is the Water Intrusion Pressure (ASTM F 1671, ISO 811). The measures obtained with this method often show a certain correlation with contact angle values. Usually water is chosen as standard testing liquid.

In order to complete the above experience, the same 11 water/acetone solutions defined for the contact angle measures were also used to perform "Water" or better Liquid Intrusion Pressure tests. This imposed some change in the method and equipment. A dedicated PTFE test cell was therefore used. The sample is 28 cm^2 and the pressure reading is done at first droplet intrusion.

Table 1. Water/acetone solutions used for dynamic contact angles measurements

Solutions		Surface tension
Acetone (%)	H_2O (%)	[mN/m]
100	0	24,62
90	10	26,24
80	20	29,30
70	30	30,37
60	40	31,43
50	50	33,72
40	60	36,01
30	70	39,06
20	80	44,25
10	90	57,79
0	100	71,32

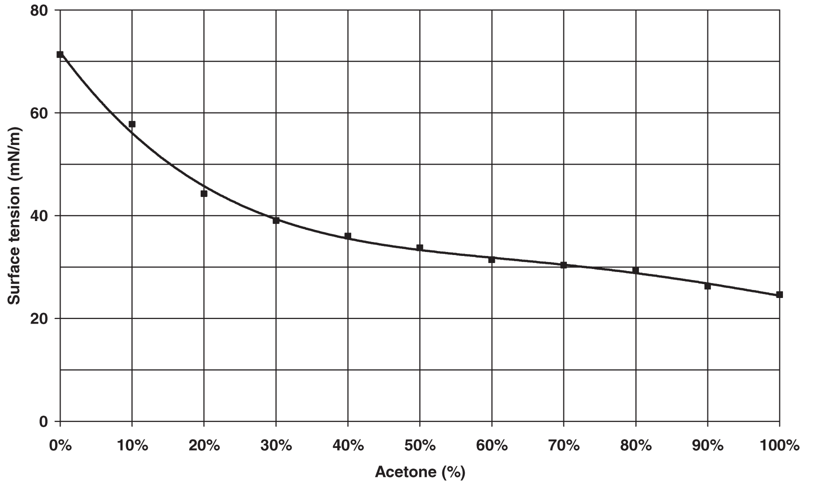

Figure 2. Surface tension of the water/acetone solutions used for dynamic contact angles measurements.

RESULTS AND DISCUSSION

PA Meshes

In Fig. 3 the contact angle values measured on hydrophobic PA fabrics with different mesh opening and open area are showed in function of the surface tensions of the reference solutions, together with the curve of one of the mesh without the hydrophobic coating. In the graph a number of vertical stripes show the surface tension value of the fuels interesting for the final application. These are completed by the area related to the water, which extends between 65 and 72 mN/m in order to consider the presence of mineral ions and contaminants that are able to decrease the surface tension. These elements will help in understanding how the mesh works for water and fuel separation.

Ideally, the material should be highly hydrophobic against water (contact angle $\gg 90^\circ$) and wettable by fuels (contact angle $\ll 90^\circ$).

The untreated mesh has a curve always under the wettable limit.

For PA items with hydrophobic coating, we can observe a repellent performance of all the samples for surface tension values above 35 mN/m. On the contrary, liquids with surface tension lower than 35 mN/m are always able to wet even the hydrophobic materials and therefore should be able to flow through them (which is the goal of water/fuel separation). In fact the hydrophobic PA meshes get contact angle values between 20 and 70° against all the liquid on the left of the graph; on the other side the contact angles with the liquids having high values of surface tension are between 120 and 145°.

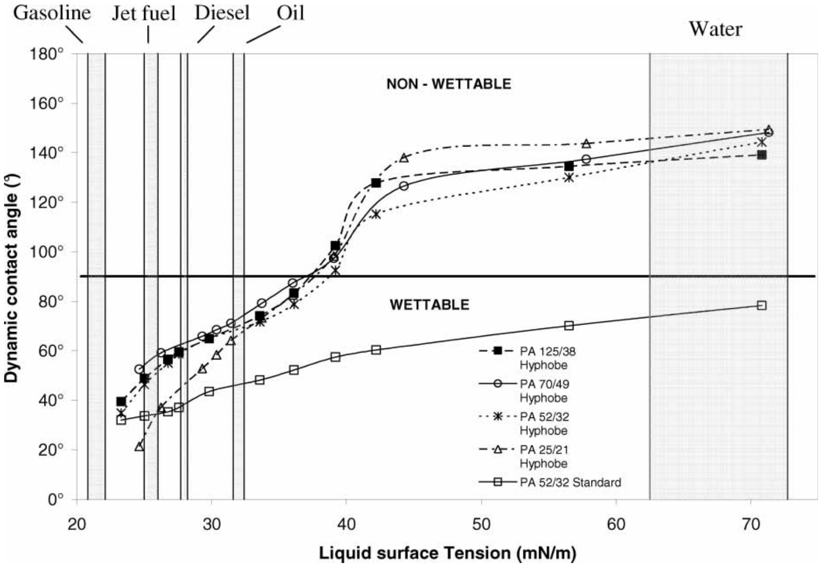

Figure 3. Dynamic contact angles measured on PA meshes for different liquid surface tension.

Therefore we have to expect a very "selective" wettability, useful to separate water from fuel during the final use of the filter. Figure 3 shows also the effect of surface roughness of PA meshes on their performances. Wenzel showed that roughness makes a significant contribution to the wetting behaviour of a solid surface (10). He showed that the apparent liquid contact angle at a rough surface, θ_r, is related to Young's equilibrium contact angle, θ_e, by

$$\cos \theta_r = r \cos \theta_e \tag{1}$$

where r was the ratio between the real area in contact with liquid and the geometrical area of the solid surface. Since r $>$ 1 for a rough surface, Wenzel's model leads to two different behaviours. If $\theta_e < 90^\circ$, θ_r goes toward 0°; instead, when $\theta_e > 90^\circ$, θ_r goes toward 180°.

We calculate the ratio r for the different PA meshes of Fig. 3. The surface roughness of the coated PA monofilaments is the same for all the meshes we have investigated. Hence, the real area of the PA meshes in contact with the liquid depends on the PA monofilaments diameter and on the mesh opening (the distance between two adjacent threads). PA 25/21, the mesh with the smallest monofilament diameter (30 μm) and the smallest mesh opening (25 μm), showed the highest value of r (1.25). The effect on the hydrophobic performances of this mesh showed in Fig. 3 was in agreement with equation (1). For contact angle values greater than 90° (liquid surface tension higher than 35 mN/m), the curve of this mesh lies above the curves of meshes with smaller r values (increased liquid-repellence). Instead, for contact angle values lower than 90° (liquid surface tension lower than 35 mN/m), the curve of this mesh lies under the curves of meshes with smaller r values (increased wettability). In this way the surface roughness of this mesh makes it very useful for fuel-water separation application.

PET Meshes

In Fig. 4 the contact angle values measured on hydrophobic PET fabrics with different mesh opening and open area are showed in function of the surface tensions of the reference solutions, together with the curve of one of the mesh without the hydrophobic coating.

Similar to what we observed with the not-treated PA mesh, the untreated PET mesh has a curve always under the wettable limit.

On the contrary, hydrophobic PET meshes show a repellent behavior for the large majority of the liquids. The transition point is very close to the left side of the diagram and therefore these materials are able to stop a wide range of liquids, even with very low surface tension. Therefore, these materials can be described as oleophobic and hydrophobic. As a consequence, their use is quite different: they are not intended for water/fuel separation and on the contrary they can be a very effective oleophobic protection for any air intake in the most various applications.

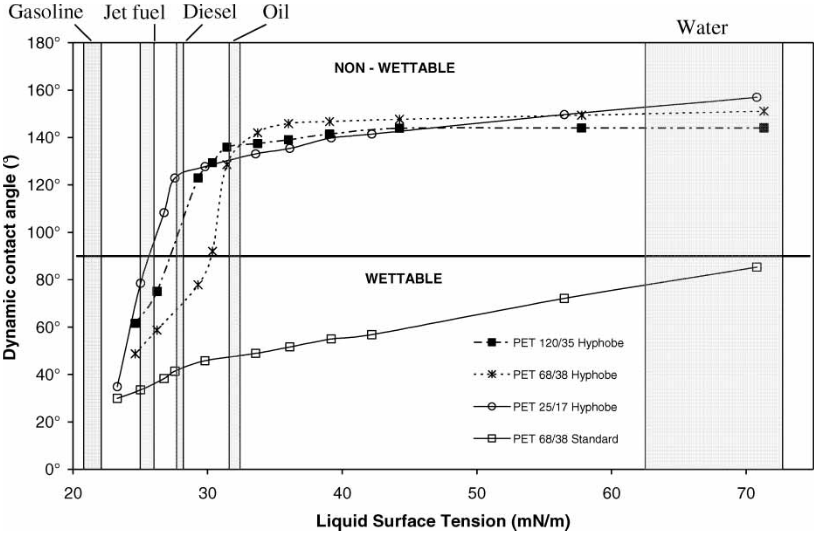

Figure 4. Dynamic contact angles measured on PET meshes for different liquid surface tension.

Water Intrusion Pressure

The contact angle method is able to describe the wetting properties of the materials (polymer + coating) but not the properties related to the construction of the woven meshes. With no surprise we discover that the contact angle curves of fabrics of the same material are very similar to each other, especially for polyamide meshes. On the contrary the water intrusion pressure values are very different even inside the same family.

In fact, the finest mesh performs three or four time better than a coarser fabric of the same polymer and with the same coating, as we will see in the following graph.

This means that we have to consider also another important effect that governs this phenomena: the pore size, i.e. the "mesh opening" of the woven fabric. We can see from experimental results that liquid intrusion pressures decrease when the mesh opening becomes higher, as anyone may expect. For instance Fig. 5 shows the intrusion pressure values for three PET meshes with hydrophobic coating having a wide mesh opening variation, from 120 μm down to 25 μm. The liquid intrusion pressure has almost the same trend thus increasing by more then three time when shifting to the smallest mesh opening. Moreover, the three curves fall down to zero almost at the same value of liquid surface tension. Finally, we discover that the shape of the intrusion pressure curve of each material is very similar to the hydrophobic portion of the contact angle curve of the same material, as shown in Fig 6. We can therefore conclude that the liquid intrusion pressure curve of a material could be define as a product of two factors: the first is a scale factor related to the mesh opening, the second is related to the hydrophobic performances of the material against liquids having different surface tension (hence, is related to

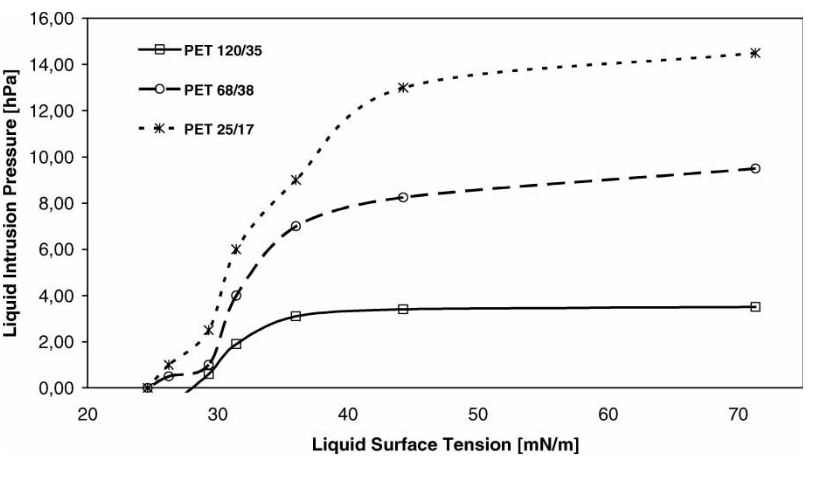

Figure 5. Liquid intrusion pressures measured on different PET meshes.

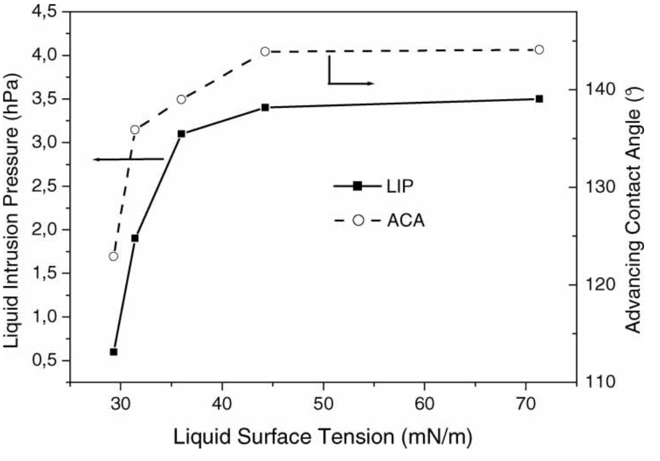

Figure 6. Comparison between liquid intrusion pressure and hydrophobic portion of the contact angle curve for PET 120/35.

the contact angles values in the hydrophobic portion of the curves in Fig. 3 and Fig. 4).

The liquid intrusion pressure results have been analyzed with the Laplace-Washburn equation:

$$P = -\frac{2\gamma \cos \vartheta}{R} \quad (2)$$

where P is the pressure of the liquid for which intrusion occurs, γ the total liquid surface tension, θ the liquid contact angle and R the pore radius. From equation (2) we calculate the theoretical "pore size" R_t of our meshes, for different the WIP values measured with the different water/acetone solutions. Then, we compared the theoretical pore size with the equivalent pore size of the meshes:

$$R_{Eq} = \sqrt{\frac{L^2}{\pi}}$$

where L is the mesh opening. For all the PA and PET meshes we found that $R_t > R_{Eq}$. In particular, the calculated R_t values lies between 2.5 R_{Eq} and 10 R_{Eq}. On the other hand, when R_{Eq} was introduced in Eq. (2), the resulting liquid intrusion pressures were several times higher than the experimental values. These discrepancies could derive from a limited applicability of the Washburn law, which can be applied with water only for pores with radius $R \leq 10\ \mu m$ (the maximum radius for which the water front has a spherical form) (12). More complex models have to be developed in order to better correlate the liquid intrusion pressure results with the mesh opening and the hydro repellence of our meshes.

CONCLUSIONS

The new methodology proposed in this work helps in better understanding of the wetting phenomena. We demonstrated that the use of a range of calibrated solutions is useful to analyze the wettability of meshes. With this study we are able to give a direct support for the final applications. We analyzed two family of coated and uncoated woven meshes. The first family, PA meshes, has a well defined transition point for selected wettability and consequently is an appropriate choice for water/fuel filtration. The second family, PET meshes, show a very strong repellent behavior and we can consider them as oleophobic materials. This study is helpful for refining new media that have to deal with new generation fuels (with surface tension modified by presence of additives). We verified that this set of test liquids can be used also in a modified water intrusion test apparatus with meaningful results. We give a first interpretation of the intrusion pressure results, finding the elements that influence the liquid intrusion pressure values. One element is a scale factor depending on the mesh opening (inverse trend) and the second one is related to the contact angles values in the hydrophobic portion of the surface tension/contact angle curves.

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