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Water drop movement on woven fiber mat surfaces due to flow of diesel fuel

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A B S T R A C T

Fuel contamination by water is one of the major factors of engine failures. Separation of water from diesel fuel is often achieved by coalescing or depth filter media. The separation performance is strongly related to the motion of drops on the surface and in the depth of a filter medium. The dynamics of the motions of drops on a filter surface are influenced by many factors such as the wetting properties of the media. Direct observations of drop movements on fiber surfaces are not well documented. Of particular interest in this work are the dynamics of drops on surfaces of hydrophobic mats that resist drop movement into the interior of the mat, forcing the drops to move on the surface of the mat. Such materials function as barriers to the dispersed phase and allow the continuous phase to move through the mat.

In this paper, the motions of water drops were studied on surfaces of mats woven of polypropylene, nylon and Teflon™ (ie, polytetrafluoroethylene) fibers. Pore sizes of the mats ranged from 100 to 1000 μm and drop sizes ranged from 200 to 6000 μm. The flow of ultra low sulfur diesel fuel parallel to the mat surface provided a drag force that induced the movement of the drops. The effects of surface wettability, flow velocity, drop size, fiber size, fiber mat pore size, fiber mat orientation were considered. A correlation for a drag coefficient to estimate the average velocity of drops moving on the woven mats surfaces was derived from the flow and the material's characteristics. In addition, another correlation was obtained for estimating the minimum velocity, or minimum Reynolds number, required to initiate the drop motion on the woven mat surfaces.

1. Introduction

The interactions between water drops and hydrophobic woven fiber mats are of interest in many applications such as separation of water drops from oil, dehumidification, and rain coats [1]. Depending on the applications, the materials, the mat structures, and the fluid flow directions, the drops may pass through a mat or move across the surface of a mat. In this work the movements across hydrophobic mats by water drops submerged in diesel fuel are investigated. The motivation of this study is to create better understanding of hydrophobic membranes to separation of water drops from oil.

The presence of water in diesel fuels in the form of droplet dispersions can cause many problems such as plugging of fuel injectors, reduction of fuel flow rate, reduction of fuel lubricity and corrosion of engine parts [2]. Hence, removing water contamination from diesel fuel is important to the maintenance and life of diesel engines. When a water drop size is larger than 100 μm, the water drops can be effectively removed by gravity settling [3]. However, dispersions of drops smaller than 100 μm are more difficult to separate and often require the use of coalescing depth filters [4] or a membrane technology [5].

Madani et al. [6] observed that the motion of a drop on flat surface can be characterized as different behavioral regimes (a) sliding, (b) deforming, and (c) detachment, depending on the drop size, the drop fluid properties, the continuous fluid phase properties, and the flow conditions. Under appropriate conditions, water drops easily roll or slide across the hydrophobic surfaces and leave behind little to no residue [7,8]. Daniel and Chaudhury [9] found that drops on surfaces with spatially varying wettability tend to move toward the more wetting part of the surface with speeds of 1–2 mm/s on a gradient surface. Subramanian et al. [10] developed estimates the speed of drops on surfaces with a wettability gradient. Gather et al. [11] observed water drops moving by gravity on inclined hydrophobic surfaces. Sheng and Zhang [12] investigated water drop motions on ratchet-like superhydrophobic surfaces. Bhushan and Jung [13] observed the static contact angles on the

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Nomenclature

A	area of contact between the drop and the mat (μm^2)
A_{drop}	projected area of the drop in the direction of diesel flow (μm^2)
C_D	drag coefficient due to the diesel drag around the drop
C_{mat}	drag coefficient due to the drop on the mat
Ca	Capillary number
d_A	length of drop measured horizontal to the mat (μm)
d_c	diameter of contact area (μm)
d_f	diameter of fiber (μm)
d_{pore}	diameter of pore on the mat (μm)
d_L	length of drop measured perpendicular to the mat (μm)
F_{cap}	capillary force (N)
F_{cl}	contact line force (N)
F_D	drag force acting on the drop due to diesel flow (N)
F_f	drag force of moving drop on fiber (N)
La	Laplace number
Re_{ULSD}	Reynolds number of the diesel
Re_{mat}	Reynolds number of the drop on the mat
t	time scale (s)
U	drop velocity (m/s)
V	gas velocity (m/s)

Greek symbols

α	angle of one fiber relative to the flow direction
γ_{water}	surface tension of the water drop (N/m)
μ_{diesel}	viscosity of diesel (kg/(m s))
μ_{water}	viscosity of the water drop (kg/(m s))
θ_a	advancing contact angle between the drop and the mat, deg
θ	static contact angle between the drop and the mat, deg
θ_r	receding contact angle between the drop and the mat
ρ_{diesel}	density of diesel (kg/m^3)
ρ_{water}	density of water (kg/m^3)

patterned silicon surfaces and measured adhesive forces and coefficient of friction with the help of atomic force microscope. However, to our knowledge, correlations for the motions of drops across woven mats due to the drag force by liquid flow have not been reported.

The separation efficiency of a filter is strongly related to the dynamic motions of drops in a filter medium. Fundamental drop motions in a filter include movements of drops on single fibers, at junctions of two fibers, on mat surfaces, through pores of a thin mat, and with the depth of a thick fiber mat. The motion of drops on the surface of a filter is relevant to understanding the rate of liquid drainage from a filter. Drops draining from the filter are typically much larger than the emulsified drops, with sizes ranging from tenths to tens of millimeters in diameter.

In this work, the movements of water drops across surfaces of woven mats of polypropylene (PP), polyamide (nylon), and polytetrafluroethylene (PTFE) fibers were observed due to the drag flow of ultra low sulfur diesel (ULSD) fuel. The water droplets moved when the ULSD drag force exceeded the motion resistance forces that tended to hold the drops stationary. The ULSD flow rate was gradually increased until water drop movement was observed. The minimum ULSD velocity, or minimum Reynolds number, at which the drop began to move, was fitted to a correlation for predicting conditions to initiate drop movement. The initial drop motion depended on the surface properties of the fiber mats, such as wettability, surface roughness and heterogeneities [14]. Another correlation was fitted to relate the drag coefficient to the Reynolds and Capillary numbers of a drop moving on the mat surfaces. This work only considered clamshell shaped drops of sizes ranging from about 200 μm to 6000 μm that sat on top of the surface of the mats and did not penetrated into the fiber mats. The drops were two to six times larger than the mat pore openings.

2. Description of experiments

2.1. Mat, liquid materials, equipment

Woven PP mats had squared shaped pore opening with sides of length 105, 210, 500 and 1000 μm (referred as samples PP105, PP210, PP500 and PP1000, respectively) were purchased from Spectrum Labs. The nylon and PTFE mats had parallelogram shaped openings. The diagonal lengths were 1080 μm and 490 μm for the nylon mats and 890 μm and 520 μm for the PTFE mat. The mats were cleaned prior to the experiments by sonication in distilled water, and dried in an oven to remove moisture. The thin glass fiber media (used as laminarization media) were supplied by Hollingsworth & Vose Company.

The liquids used in this study were ULSD (purchased locally) and deionized water (DI water). Some of the properties of these two liquids are summarized in Table 1. The equipment used in the experiments included a custom made Plexiglas holder, a flow meter (Cole Parmer, 034-10ST), a pump (Fasco Industries, Inc), a CMOS high-speed camera (Mikrotron MC 1310), a drop shape analyzer with camera(DSA20E Krüss GmbH), microscope (OLYMPUS, SZ-PT), and spin coater (Laurell technologies corporation, WS-400B-6NPP/LITE/AS).

2.2. Experiment setup

Fig. 1 shows a diagram of the pressure-driven flow device. ULSD was pumped through a flow meter and into a thin-slit channel holding the test mat and the water droplets. The body and cover of the holder were machined from Plexiglas. The flow channel was 4 mm deep, 3.5 cm wide, and 9 cm long. The test mats were positioned on the bottom of the channel and secured in place using an acrylic tape. To distribute the flow over the cross section of the channel, a glass fiber mat was positioned near the inlet of the channel as a flow-laminarization mesh.

A water droplet was injected with a calibrated syringe and needle into the channel and onto the sample may by inserting the needle through a small port located on the top cover. With the help of the calibrated scale of the syringe, the drop volume and size was controlled. After injecting the water drop, the injection window was sealed by an acrylic tape. The channel was illuminated from below, and the movements of the drops on the woven mats were recorded by using the high-speed camera from above. Simultaneously, the movements of the drops also were recorded from a side view by the camera of the DSA20E.

Table 1
Physical properties of reference liquids at 20 °C.

Liquid (Source)	Density (kg/m^3)	Viscosity (cP)	Surface tension (mN/m)	Boiling point (°C)
ULSD (Purchased locally)	870	1.4	29.83	180–360
DI water (Obtained by ion exchange, 0.1 S)	1000	1.02	73.5	1000