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Barrel shaped droplet movement at junctions of perpendicular fibers with different orientations to the air flow direction

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ABSTRACT

Droplet movements on surfaces are of significant interest in a wide range of practical applications. In contrast to the widely studied motion of droplets on rough and smooth surfaces in a flat configuration, knowledge of the motion across fiber junctions is sparse, despite its significance in filters. Crossed fibers at various angles to flow are a fundamental structure within a complex fibrous medium. This work presents the experimental results of a microscopic study of liquid droplet movement on crossed fibers when subjected to air flow. The crossed fibers were positioned to create different angles, within a plane, relative to the airflow direction. Crossed fibers at various angles to flow are a fundamental structure within a complex fibrous medium. The liquid droplets were placed on the intersection point using a previous method developed by the authors for single fibers. A comparison was made between different fiber layouts in terms of Reynolds number of the gas flow. A mathematical correlation for the minimum Reynolds number of gas at which the droplets began to move was developed. This correlation predicts the gas flow conditions required to start the movement of drops at the fiber junction.

1. Introduction

The study of motions of droplets on solid surfaces has received significant attention in literature. Examples include motions of a drop on a solid surface due to a wettability gradient [1] and temperature gradient [2]. Cylinders, amongst other geometries, are of considerable importance since fibers are a very common material in industrial applications [3,4], particularly in fibrous filter media [5]. While much work has been undertaken on the interaction of liquid droplets with flat surfaces, few works have investigated the behavior of droplets on fibers. Some works report on the evaluation of the force required to move a liquid droplet along oleophilic [6] and oleophobic [7] fibers. Experimental and theoretical evaluation of the detachment force due to interfacial tension effects has been carried out [8]. Some authors have discussed observation and modelling of droplets on vertical fibers subjected to gravitational and drag forces [9], and determined drag correlations for axial motion of drops on fibers [10]. The axisymmetric shape and the motion of a droplet on crossed fibers due to the gravitational force have also been described [11]. However, most of the previous works have focused primarily on single fibers parallel or perpendicular [12] to the flow direction, or the effect of fiber orientation on fiber wetting processes [13]. Few works have considered the conditions for the movement of liquid droplets on crossed fibers. To understand the movements of the droplets attached to the fibers in a fibrous structure, it is important to develop theories and correlations that allow exploration of the relationships existing between various parameters and forces acting on the droplets for fibers with different orientations.

Theoretical modelling will be reported in the future. This work focuses on experimentally relating the Reynolds number of a flowing gas and the effect of the drag force of flowing air on the behavior of droplets at junctions of perpendicular fibers having different orientations relative to the air flow direction. Through dimensional analysis a mathematical correlation for the minimum Reynolds number to initiate drop movement was proposed and fitted the Laplace number and other parameters. To extend the correlation, a range of fiber materials, fiber sizes, and liquid materials were evaluated in the experiments. Also, it is worth noting that the results were restricted to the barrel shaped droplets whose geometries were not strongly influenced by gravity.

2. Theory

Prior works show droplets tend to stay on a fiber until the force from the flowing gas is sufficient to detach the droplets. Fig. 1 shows an idealized spherical droplet at a junction between two perpendicularly oriented fibers exposed to the air flow. The air flow direction lies in the same horizontal plane as formed by the two

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Nomenclature

d_f	diameter of fiber (μm)	γ	surface tension of the liquid droplet (N/m)
d_L	diameter of droplet (μm)	μ_l	viscosity of the liquid droplet (kg/(m s))
La	Laplace number	μ_{gas}	viscosity of gas (kg/(m s))
Re_{gas}	Reynolds number of the gas	θ	contact angle between the droplet and the fiber
$Re_{gas\ min}$	minimum Reynolds number of the gas to start droplet motion	α	angle of one fiber relative to the flow direction
		ρ_l	density of the liquid droplet (kg/m^3)
V	gas velocity (m/s)	ρ_{gas}	density of gas flow (kg/m^3)

fibers. One of the fibers has the smallest angle relative to the air flow, 30 deg, and this configuration is labeled as the “30 deg” case.

As explained in a prior work [14], the probability of a droplet moving or not on a fiber is considered to be a function of variables such as static contact angle, surface tension, fluid properties, and geometric dimensions. The fluids are assumed to be Newtonian with constant densities and viscosities.

$$\text{Probability} = f(\rho_{gas}, \mu_{gas}, \rho_{liq}, \mu_{liq}, \cos\theta, \cos\propto, \gamma, V, d_L, d_f) \tag{1}$$

Using the syringe approach [14], the size of the droplets can be controlled. Therefore, droplets that were large enough to be moved by the air drag force were placed on the fibers, meaning the probability is unity. Also, the probability function is assumed to have a power law form.

$$1 = a\rho_{gas}^{b}\mu_{gas}^{c}\rho_{liq}^{d}\mu_{liq}^{e}(\cos\theta)^{f}(\cos\propto)^{g}\gamma^{h}V^{i}d_{L}^{j}d_{f}^{k} \tag{2}$$

where the coefficients $a, b, \ldots, k$ are experimentally fitted constants. The relevant Reynolds and Laplace numbers are

$$Re_{gas\,min} = \frac{\rho_{gas} d_L V}{\mu_{gas}} \tag{3}$$

$$La = \frac{\rho_{liq} d_f \gamma}{\mu_{liq}^{2}} \tag{4}$$

where $Re_{gas\ min}$ is the ratio of the gas inertial forces to the viscous drag forces and La is the ratio of the interfacial forces to the viscous drag force between the droplet and the fiber. Applying dimensional analysis [15,16] the important variables were grouped into the Laplace and Reynolds numbers as follows.

$$Re_{gas\,min} = ALa^{B}(\cos\theta)^{C}(\cos\propto)^{D}\left(\frac{d_f}{d_L}\right)^{E}\left(\frac{\rho_{gas}}{\rho_{liq}}\right)^{F}\left(\frac{\mu_{gas}}{\mu_{liq}}\right)^{G} \tag{5}$$

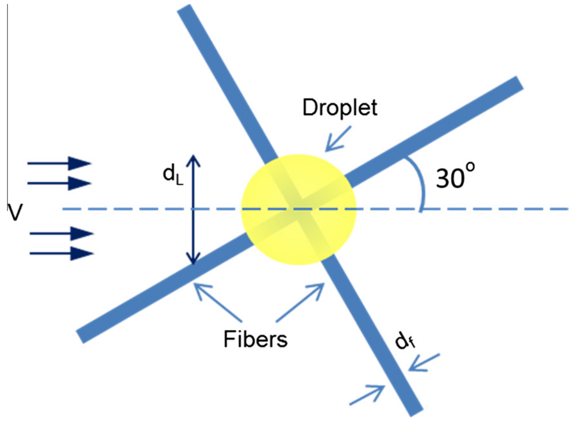

Fig. 1. The schematic of a droplet on crossed fibers in 30 deg case. The air flow indicated by the arrows has velocity V in a direction that forms a 30 deg angle with one of the fibers.

where $A, B, \ldots G$ are constants to be determined from experimental data. $Re_{gas\ min}$ is the gas phase Reynolds number for the minimum gas velocity needed to initiate droplet motion.

3. Materials and methods

3.1. Fibers and test liquids

Three different liquids were tested to give a range of contact angles on the fibers. Viscor 1487 was obtained from Rock Valley Oil & Chemical Company, WD-40 from WD-40 Company, and Ultra Low Sulfur Diesel (ULSD) was purchased locally. Physical properties of the test liquids are listed in Table 1. Nylon and polypropylene fibers with different sizes were tested in the experiments. The fibers were supplied by Minifibers Inc.

3.2. Experimental set-up

The crossed fibers experiments were carried out using a specifically designed test device [1]. Fig. 2 shows the flow diagram of the experiment. Pre-filtered house air flowed through a flow meter and into a thin-slit channel holding the test fibers and droplets. The air flow rate was gradually increased until the droplets moved off of the fiber crossing junction. The movement of droplets was recorded by a high speed camera capable of producing 1000 frames per second.

4. Results and discussion

4.1. Detachment of droplets from fibers

In this work, different angles of one fiber (the fiber with angle less than or equal to 45 deg) relative to the flow direction were considered. Fig. 3 shows the different fiber orientations for 0, 30, and 45 deg used in the experiment. Images were taken using a microscope camera. The angle between two fibers remained the same (90 deg) while the angle of one fiber was changed relative to the flow direction in the plane parallel to the flow direction. Other angles were tested but are not shown in Fig. 3.

As the air flow rate increased, the droplets started to leave the intersection. In the zero deg case in Fig. 4(a), the droplets detached from the junction but remained in contact with the fiber parallel to the flow direction. In the other two cases, the droplets left the intersection point and detached from both fibers as soon as the

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

Liquid	Density (g/cm^3)	Viscosity (cP)	Surface tension (dynes/cm)	Vapor pressure (kPa)
Viscor 1487	0.83	0.8	28.34	0.2
Ultra Low Sulfur Diesel (ULSD)	0.87	1.4	29.83	0.07
WD-40	0.82	5	31	0.01