**Drag Correlation of Drop Motion on Fibers**

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**Abstract**

The objective of this project is to develop a drag coefficient correlation for axial motion of droplets on fibers. The work includes effects of vibration induced motion droplet motion and coalescence. A significant amount of literature describes the mechanisms of droplet capture, coalescence, and drainage from filter media and models are developed at a scale that accounts for the liquid held in the filter through averaged parameters such as saturation. But there is a lack of literature on the behavior of individual drops which ultimately controls the coalescing filter performance.

The study of drop motion on fibers is of scientific and economic interest for many possible applications like printing, coatings, drug delivery and release, and filters to remove or neutralize harmful chemicals or particulates from air streams.

An experiment is designed for the couette air flow with a rotating surface for air flow past the fiber and drops to produce linear laminar air velocity field. Drops are attached to the fibers by exposing the fibers to liquid aerosols. A 3-D Fluent model for the couette flow device is run for simulations to evaluate the air velocity profile to ensure the velocity field is in laminar flow.

In this paper the experimental drag coefficient verses Reynolds number data are compared for 1-D and 3-D cylindrical drop models. The results show the 1-D models are inadequate to predict the drag coefficient but do show the same general trends.

Key Words: Drops, Drag Coefficient, Fibers, Filtration

## Background

A significant amount of literature describes the mechanisms of droplet capture, coalescence, and drainage from filter media [1-11]. Most models of the coalescence process are developed at a scale that accounts for the liquid held in the filter through averaged parameters such as saturation. The averaged parameters do not explicitly account for individual drop sizes or motion of individual drops. Significantly improved models have been developed for liquid drainage from filters through correlations of the average saturation with the Capillary and Bond numbers [1], but there is a lack of literature on the movement of individual drops on fibers. The behavior of individual drops ultimately controls the coalescing filter performance.

The interactions and coalescence of individual drops attached to fibers, the shapes of drops on fibers, and the locations of the drops relative to the fiber junctions are reported in literature [3,5,9]. Briscoe *et.al.* [11] studied the growth of individual drops by exposing a single fiber oriented normal to the flow of a gas stream containing a liquid emulsion. In their model and experiments the drops on the fiber were essentially stationary, except when coalescing with a neighboring drop.

A number of papers that report on stability, spreading, and shape of droplets on fibers [17-19]. Mullins [20] studied the particle capture process for different shape of droplets on a microscopic scale in filters. Few papers in literature discuss movement of drops on fibers, Yarin et al [21], describes the motion of droplets on fibers due to an applied temperature gradient on the fiber.

## 1-D Cylindrical Model and Experimental Approach

With appropriate simplification, we can mathematically model the drag force between a drop and a fiber [22]. The effects of wetting or spreading of the drop liquid and surface properties of the fibers are not studied in this work, but are expected to influence the drop migration. The force balance is applied for the interactions between the drop and the fiber and the fluid surrounding the drop

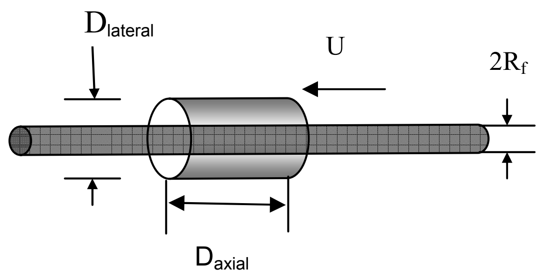


Figure 1. The system geometry with a stationary liquid cylinder through which a fiber moves with velocity U.

A force balance on the drop on the fiber in Figure 1 is applied to derive an expression for calculating the drag coefficient from the experimental measurements. The general force balance is

$$\frac{d(MU)}{dt} = F_{fluid-drop} - F_{drop-fiber} + F_{gravity} \tag{1}$$

where $F_{gas-drop}$ is the drag force of the fluid flowing past the drop and $F_{drop-fiber}$ is the drag force acting on the drop due to the drop fiber interactions.
At steady state and for horizontal motion, we conclude

$$F_{fluid-drop} = -F_{drop-fiber} \tag{2}$$

The drag force acting due to the fluid flowing past the drop can be expressed as

$$F_{fluid-drop} = C_{fluid-drop} A_{drop} \frac{1}{2} \rho_{fluid} \left(V - U_{drop}\right)^2 \tag{3}$$

where $A_{drop}$ is the projected area of the drop in the direction of the air flow, $A_{drop} = \frac{\pi}{4} D_{lateral}^2$

and the drag force due to the drop fiber interactions is expressed as

$$F_{drop-fiber} = C_{drop-fiber} A_{fiber} \frac{1}{2} \rho_{drop} U_{drop}^2 \qquad (4)$$

where the area of contact between the drop and the fiber is $A_{fiber} = \pi D_{fiber} D_{axial}$ where $D_{fiber} = 2R_f$ and $D_{lateral} = 2R$ .

Equating the two forces in equations (3) and (4) we get

$$C_{drop-fiber} = \frac{C_{fluid-drop} \rho_{gas} \left(V_{gas} - U_{drop}\right)^2 D_{lateral}^2}{4 \rho_{drop} U_{drop}{}^2 D_{fiber} D_{axial}} \qquad (5)$$

Equation (5) is the working equation for calculating the drag coefficient from the experimental data. The drag coefficient can be calculated from equation (5) by knowing the data for $C_{fluid-drop}$ which is evaluated from the experiments.

## Experimental Setup

The Couette flow experimental setup is designed such that the air flows past the fiber and drops using a moving surface to develop couette flow. The couette laminar flow velocity profile is shown in Figure 1. For the flow to be laminar the Reynolds number for the channel must be less than 2000 [22].

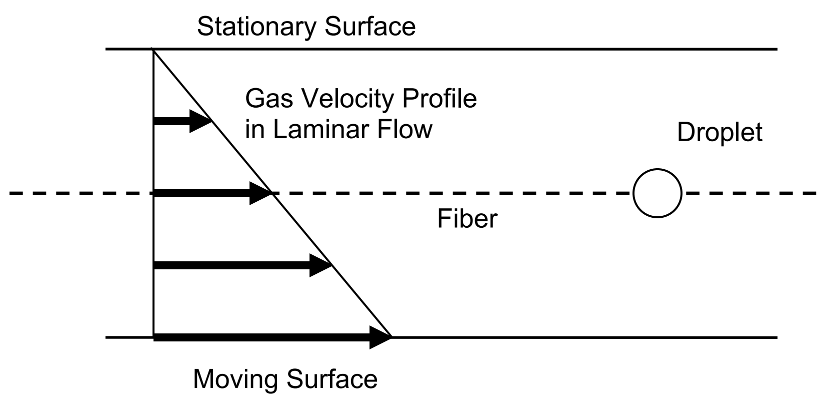


Figure 2. Laminar flow velocity profile for couette flow in a rectangular channel. The fiber and droplets are located at the center line of the space between the surfaces. At the center line the gas velocity is ½ the velocity of the moving surface. This is the velocity experienced by the drop to cause the drop to move along the length of the fiber.

In the experimental setup the fiber is attached on the Plexiglas holder with the help of screws and the drops are manually sprayed on to the fiber. A glass slide placed on the top which behaves as a stationary surface and the fiber is exposed to the rotating disk which is used to produce the air velocity which acts as a moving surface.

Ideally for this experiment the velocity profile created by the moving disk surface should be linear and laminar as indicated in Figure 2. As the fiber is located in the center of the channel, the air velocity at that location is one-half the velocity of the moving surface.

To perform a check of the velocity profile obtained from the experimental approach the FLUENT™ simulations are done for the described experimental setup. The calculated velocity profiles are shown in Figure 3. The figure shows that the y-component of the velocity gives a laminar profile for Reynolds number < 2000 but the velocity profile is not linear. It shows that the nonlinear velocity profile is obtained at the fiber location which is 0.112 times the surface velocity.

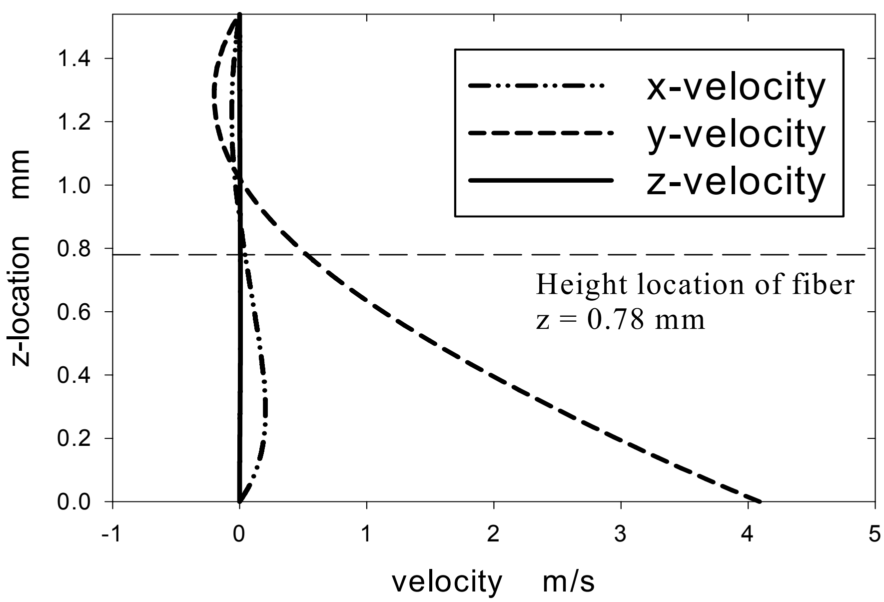


Figure 3. Flow along the vertical centerline of the cavity.

**Experimental Results**

The various liquids and fiber materials are used having different wetting properties. Fibers used in these experiments are made of glass (diameters varying from 10 to 20 microns), Nylon (diameters varying from 19 to 23 microns) and Silicon Carbide (diameters varying from 4 to 6 microns). The liquid drops consist of propylene glycol of density of 982.7 $kg/m^3$, viscosity of 0.1 N $s/m^2$, and surface tension of 3.4 N/m. The drops are observed to attach and move on the fibers as prolate spheroids attached symmetrically around the fiber.

The Sample images of the drops on fibers at different time intervals are shown in Figure 4. Images such as these are used to determine the drop velocity.

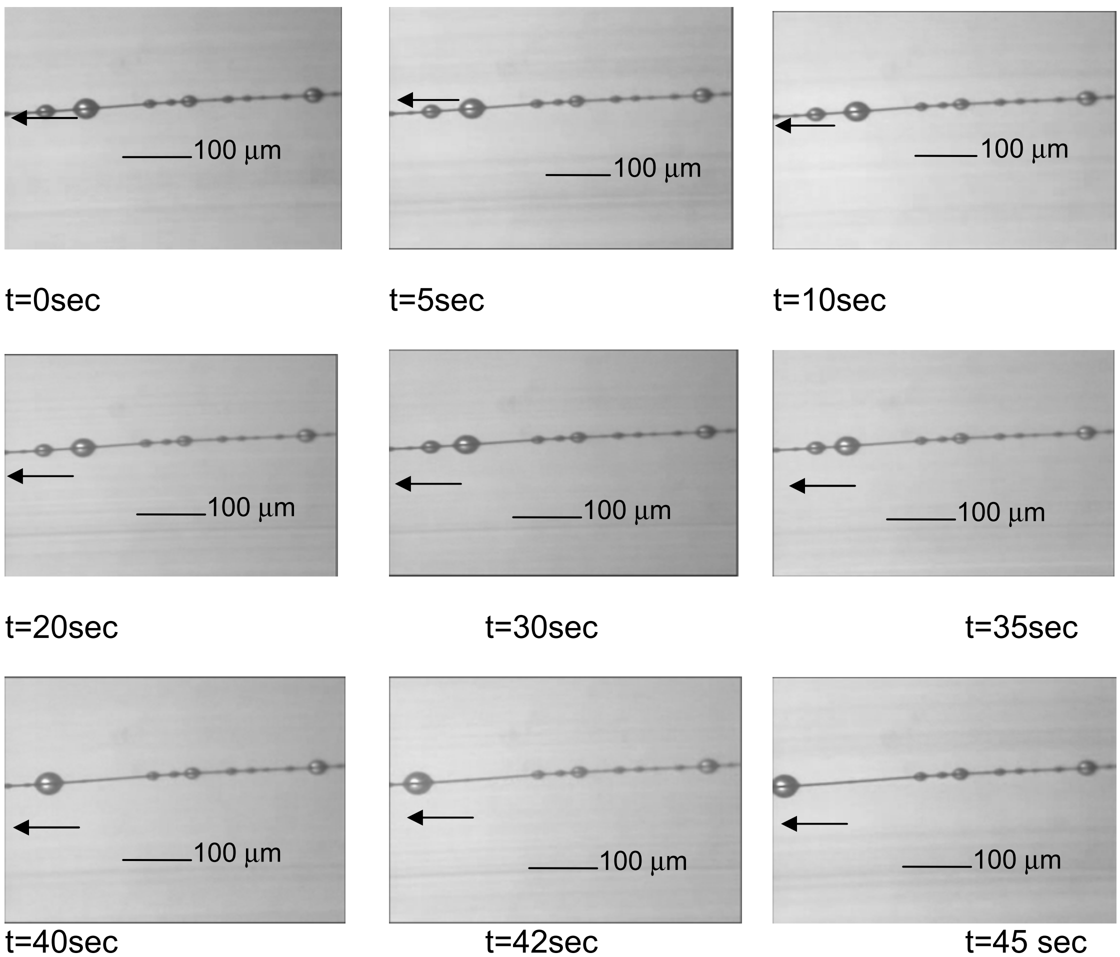


Figure 4: The figure shows the droplet of propylene glycol of diameter 39.11 microns on the Silicon Carbide fiber of diameter 4 microns moving with the drop velocity of 0.9896μm/sec and gas velocity of 414.48 cm/sec.

**Effect of Vibrations**

The drops are observed through a microscope to move or not move in a stochastic random behavior under identical conditions. In order to overcome this problem we used the effect of vibrations to move the drops in a consistent manner. The vibrations are produced in the experiment with a subwoofer positioned on the table at a distance of about 20 cm from the fiber and the frequency was varied using a frequency generator in the range of

150-180 Hz. The intensity of sound measured with the help of a sound intensity meter at 30 cm from the subwoofer was in the range of 86-90 dB. The vibrations are used to initiate drop motion. Once moving the drag of the air on the drop maintains the motion. The vibrations were not observed to affect the derived drag coefficient as seen in figure 5.

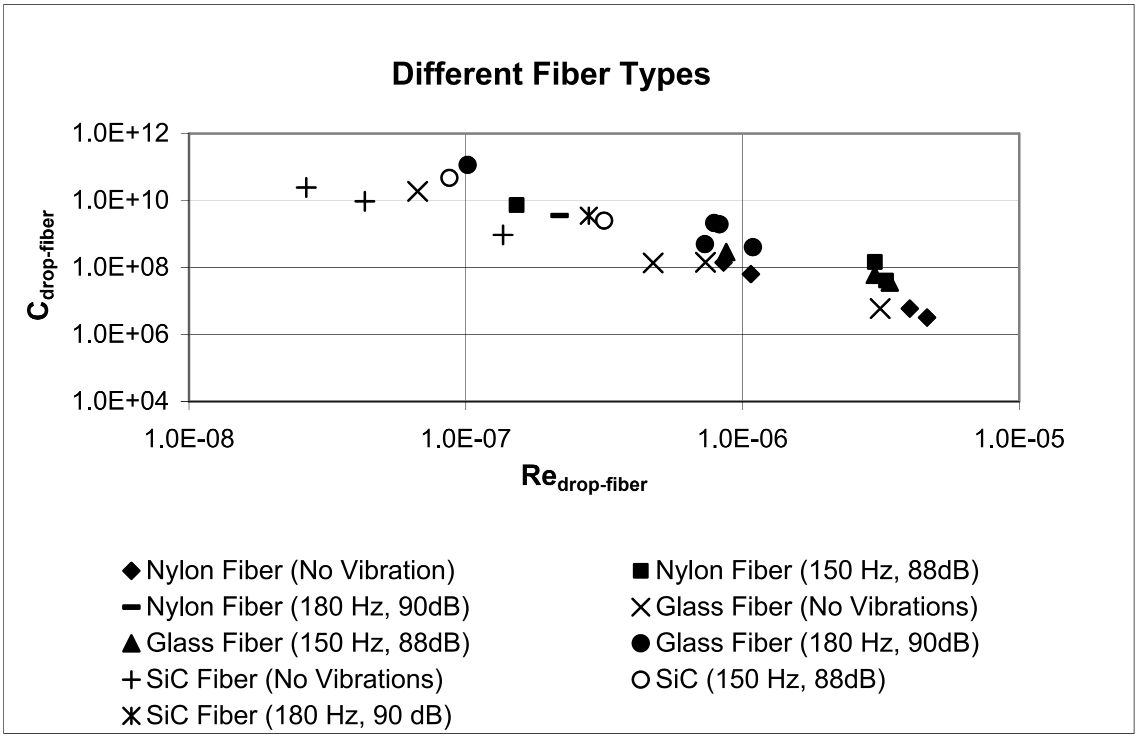


Figure 5. The graph for the $C_{drop\text{-}fiber}$ Vs $Re_{drop\text{-}fiber}$ to make a comparison for the different fiber types in the presence and absence of vibrations.

The graph in figure 5 describes that we get the same results for the drag coefficient with or without vibrations and also at different vibration frequencies. This explains that the vibrations does not change the final results but indeed helps to initiate the movement of the drops on the fiber. Also the fiber materials do not have an effect on the drag coefficient but the use of different fiber materials helps in studying the range of Reynolds number.

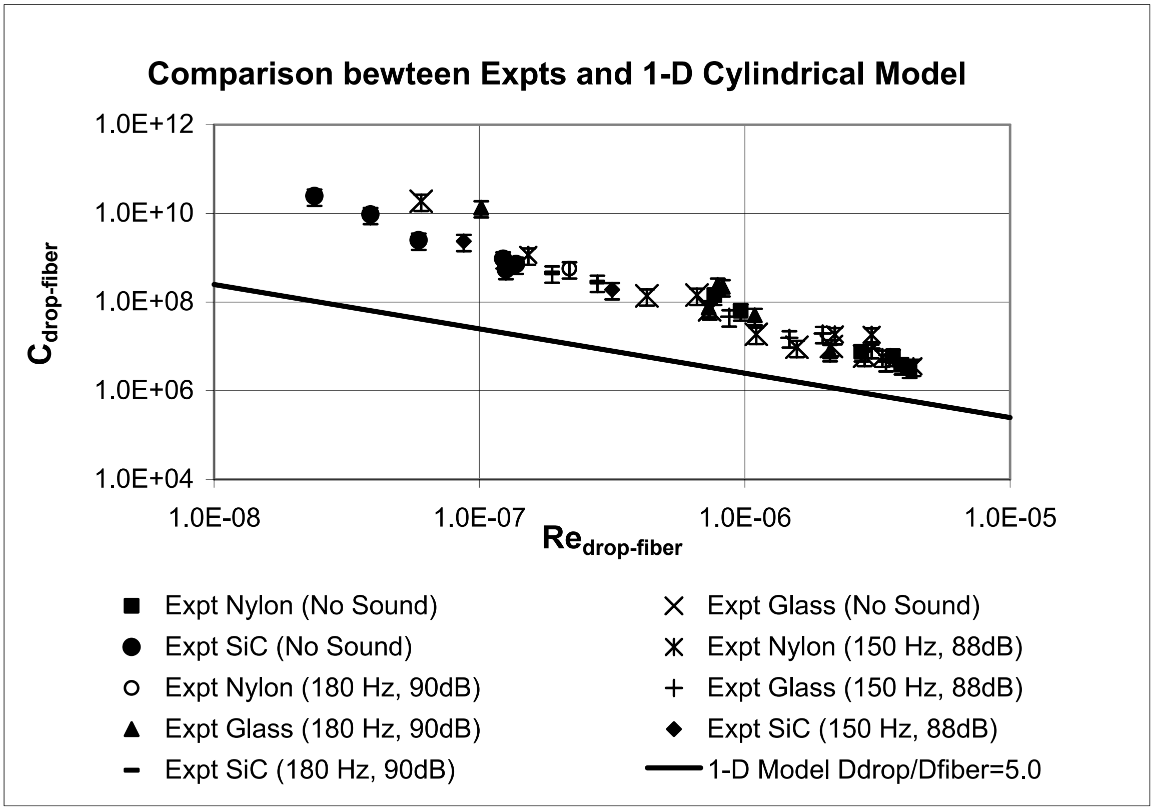


Figure 6. Comparison of the $C_{drop\text{-}fiber}$ versus $Re_{drop\text{-}fiber}$ values between the experiments measured results and the 1-D cylindrical model. The experimental data points are for drops collected on various fiber types and various sound conditions. The Ddrop/Dfiber ratio is the variable parameter which effects the drag coefficient for the 1-D cylindrical model.

### 3-D Cylindrical Fluent Model

The drag coefficient defined in equation (4) is also evaluated computationally using 3-D Fluent software. The value of $F_{fluid-drop}$ , is calculated from Fluent and in order to find the value of $C_{drop-fiber}$ . The drop shape is assumed to be cylindrical in the computational model. The 3-D model results in a good agreement with the 1-D cylindrical model.

## Conclusions

The couette flow experiments were run to correlate the drag coefficient for drop motion on several types of fiber materials. We observed that vibrations from a speaker helped to initiate the movement of the drop on the fiber but it does not have an effect on the drag coefficient. So it has been observed that the type of fiber material and sound does not effect the drag coefficient values. The 1-D cylindrical model values however were not consistent with the values from the experiments. The models need to be modified to account for surface tension effects and the geometry of the drops.

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