

# Measurement of Film Thickness on a Curved Surface by Fiber Optic Probe

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## ABSTRACT

A fiber optic sensor is developed in order to measure film thickness along a curved surface. The technique is non-invasive, which has large bandwidth and good spatial resolution (150  $\mu\text{m}$  and 300  $\mu\text{m}$ ). A “finger” type surface is used on top of which liquid is poured down in a continuing manner. Film thickness is measured with the fiber optic probe on 2 different locations along the “finger” surface. Film thickness of 163 and 79  $\mu\text{m}$  was measured near the top and in the middle of the fin surface.

**Keywords:** Fiber Optic; “Finger” Surface; Condensation

## 1. Introduction

Film thickness measurement is of paramount importance in many fields such as boiling, evaporation and condensation. In these processes, the heat flows through the film. The heat flux is inversely proportional to its thickness according to the theory (Webb [1]). The widespread use of curvilinear surfaces leads to evaporation/condensation enhancement (Kraus, Aziz and Welty [2]). The film will be redistributed on the surface into two regions: thin film and thick one. Intensive process of evaporation or condensation will be in the first region. The accurate measurements of film thickness are required to validate the models available in the literature.

Liquid films are used in a variety of industrial applications such as evaporators, condensers, cooling of computer chips, just to mention but a few. Over the years, many techniques have been developed to measure film thickness. Among these techniques it can be mentioned the needle contact method, the electrical conductance method, the capacitance method, and the interferometer method. More detailed information on these and other methods can be found in Shedd and Newell [3].

Fiber optic method is based on the reflected light from the liquid film. There are two fibers: one emitting fiber that illuminates the target and a receiving fiber which takes the reflected light from the target. Fiber optic has lots of advantages on other methods. Fiber optic is non-intrusive, which can be used to reach remote locations, can be used in harsh environment, small size and light weight, large bandwidth and high sensitivity (Gholamzadeh and Nabovati [4], Yin, Ruffin and Yu [5]). Other

than measuring the film thickness (which is the object of the present investigation), fiber optic can be used as a sensor to measure temperature, pressure, acceleration and strain (Yin, Ruffin and Yu [5]).

Fiber optics have been already used to measure film thickness in a variety of applications. Yu and Tso [6] used single and multi fiber optic to measure film thickness and orientation of a clear liquid film; they concluded that liquid films thicker than 1 - 4 mm can be measured by multi fiber and below 1 mm the single fiber should be employed. They concluded that the limitation in both cases is due to the numerical aperture of the fibers. Evseev [7] employed reflective fiber optic probes to measure film thickness at inaccessible locations and large distances from the object (10 m). Evseev used single and pair fibers as well as coaxial, hemispherical and random distributed fibers in the probe. Evseev achieved a spatial resolution of 0.2 - 0.3 mm and a band width of  $10^{-3}$  -  $10^{-4}$  with a stated accuracy of 1% - 2%. Alekseenko *et al.* [8] had developed a reflecting-type fiber optic sensor to measure the film thickness of liquid nitrogen and an aqueous ethanol solution flowing down on a vertical plate; they used single and pair optical fibers, with the latter having a variation using a glass plate glued on the end of the probe. Zaitsev *et al.* [9], Zaitsev and Kabov [10] and Zaitsev, Kabov and Evseev [11] investigated the rapture of liquid films flowing down an inclined heated plate; measurements of the liquid thickness have been done using reflective-type fiber optic. The film was flowing along absolutely flat surface in the described experiments.

Fiber optic sensors can measure smooth film thickness

with no waves. In fact, in case of wavy films reflection problems on the waves will impede making good measurements (Zaitsev, Kabov and Evseev [11]).

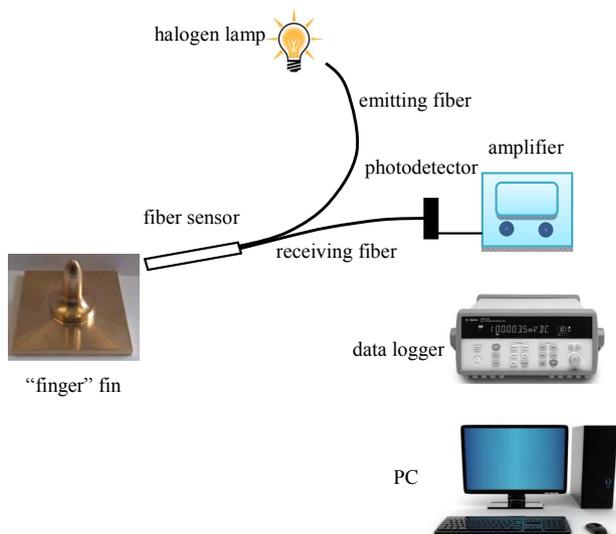
In the present work the authors use reflective-type fiber optics to measure thickness of the liquid film flowing along a curvilinear surface in 2 different locations. The shape of the curved surface (fin) has been derived to optimize condensation process which will be the subject of future research topic. The novelty of the present study is to use a non-invasive technique to measure condensate liquid thickness along a curvilinear surface. This work is relevant to condensation on top of enhanced finned surfaces.

## 2. Experimental Equipment and Setup

The experimental setup is graphically reproduced in **Figure 1**. The basic components of the setup are:

- The light source which is an halogen lamp;
- The fiber optic probe which is made of two fibers, one emitting fiber which takes the light of the halogen lamp and delivers to the target area, and a receiving fiber which takes the reflected light from the target and delivers it to the photodetector;
- The photodetector converts the light in current;
- The amplifier takes the signal from the photodetector and displays it in Amps.
- There is also an Agilent data logger connected to a PC for results visualization and data storage;
- A liquid pump which keeps the liquid recirculating and delivers the liquid through a needle on top of the finger;
- A liquid reservoir which damp vibration created by the liquid pump.

The most important component of the setup is the fiber optic. We have used two types of fibers optics. The



**Figure 1.** Experimental apparatus.

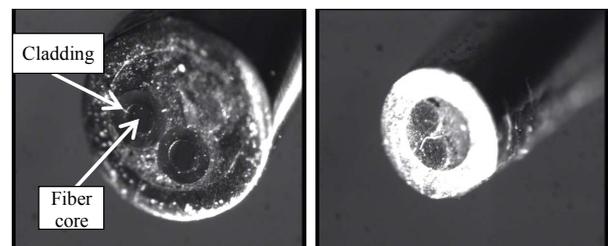
smallest used has a pure silica core of 300  $\mu\text{m}$ , a doped-silica cladding of 30  $\mu\text{m}$ , a polyimide buffer of 40  $\mu\text{m}$  and a numerical aperture of 0.22. The largest fiber has a pure silica core of 600  $\mu\text{m}$ , a doped-silica cladding of 30  $\mu\text{m}$ , a polyimide buffer of 25  $\mu\text{m}$ , and a numerical aperture of 0.22. The most delicate part of the fibers is its end. When fibers are cut they produce a rough surface which is not good if one wants to make measurements with the fibers. Therefore the ends must be carefully polished. The polishing procedure employs the use of very fine abrasive paper starting from grade 800, to grade 2000 and finishing with grade 5000. The fiber sensor is composed of two fibers inserted with epoxy resin in a stainless steel tube (1.3 mm diameter for the small fibers and 2.6 mm diameter for the large fibers). Polishing the fiber sensor must achieve good flatness and especially small roughness. It is desirable that roughness should be less than the wavelength of the visible light. For this reason abrasive diamond paste is used with grade 3  $\mu\text{m}$ , 1  $\mu\text{m}$ , 0.25  $\mu\text{m}$ , 0.1  $\mu\text{m}$ .

After polishing the fiber optic probes look like the picture reported in **Figure 2**. As can be seen for the larger fibers (600  $\mu\text{m}$ ) there is the fiber core (in glass) and the cladding. For the second fiber the cladding is too thin to be seen.

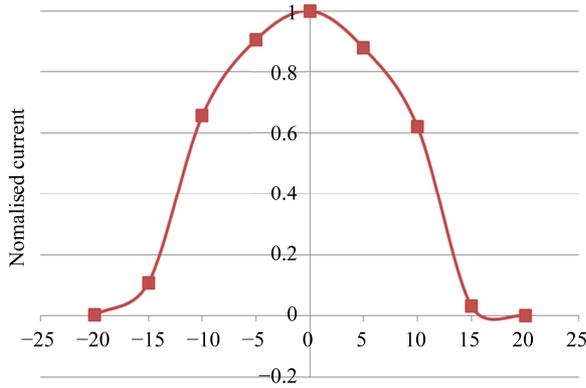
## 3. Calibration and Spatial Resolution

Before calibration of the fiber sensor is carried out the angular characteristic of fiber sensor should be checked. The procedure consists in rotating the fiber probe from the vertical orientation and measuring the reflected light from a mirror surface. At a certain angle there would be no more light captured by the receiving fiber. The angular characteristic of the two fibers employed is reported in **Figure 3**. As can be seen from **Figure 3** the fiber probe operates correctly only when the surface is perpendicular to the probe. This property will also be used in the present study to ensure that the probe is perpendicular to the curved surface: in practice the probe will be rotated till the reflected light reads a maximum, at this point it is sure that the probe is perpendicular.

The calibration is done using a pool of the same liquid (FC43) used on the fin for which the film thickness will



**Figure 2.** Details of fiber optics probes. 2.6 mm probe on the left and 1.3 mm on the right.



**Figure 3. Angular characteristic of the largest fiber optic probe.**

be measured. The pool is made of black plastic and is 40 mm deep to avoid reflection from the pool bottom. The calibration is carried out in a similar fashion than Zaitsev, Kabov and Evseev [11]. With the help of a micro screw (with resolution 5  $\mu\text{m}$ ) the probe approaches the liquid surface with steps of 50  $\mu\text{m}$ . **Figure 4** reports the calibration curves for the larger fiber probe.

The calibration is done on the finger with and without the liquid (FC43). Each curve has a “front slope”, “optical peak” and “back slope” [12]. The “front slope” is due to the fact that when the fiber probe is too close to the surface only a small portion of reflected light enters the receiving fiber; in fact, the two cores of the fibers (emitting and receiving) are 370  $\mu\text{m}$  distant from one another.

The spatial resolution of the fiber optic probe depends on the fiber core diameter ( $d$ ). In **Figure 5** the emitting fiber produces a cone of light which impacts on the surface. The reflected light can be thought of coming from a virtual light source (A); the receiving fiber (which is depicted in **Figure 5** separately from the emitting fiber tin order to improve readability) receives light from the virtual light source. The spatial resolution ( $\delta$ ) can be computed as following:

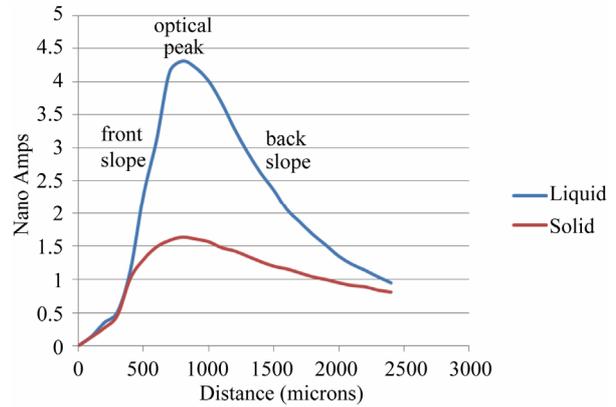
$$\begin{aligned} \delta &= y_2 - y_1 = H \tan \beta_2 - H \tan \beta_1 \\ &= H \left( \frac{x_2}{2H} - \frac{x_1}{2H} \right) = \frac{d}{2} \end{aligned}$$

$x_1$  and  $x_2$  are the distances between the middle of the emitting fiber and the boundaries of the receiving fiber.  $H$  is the distance between fibers and target surface.  $y_1$  and  $y_2$  are the projections of  $x_1$  and  $x_2$  at the target surface. Therefore the spatial resolution is half the fiber core diameter.

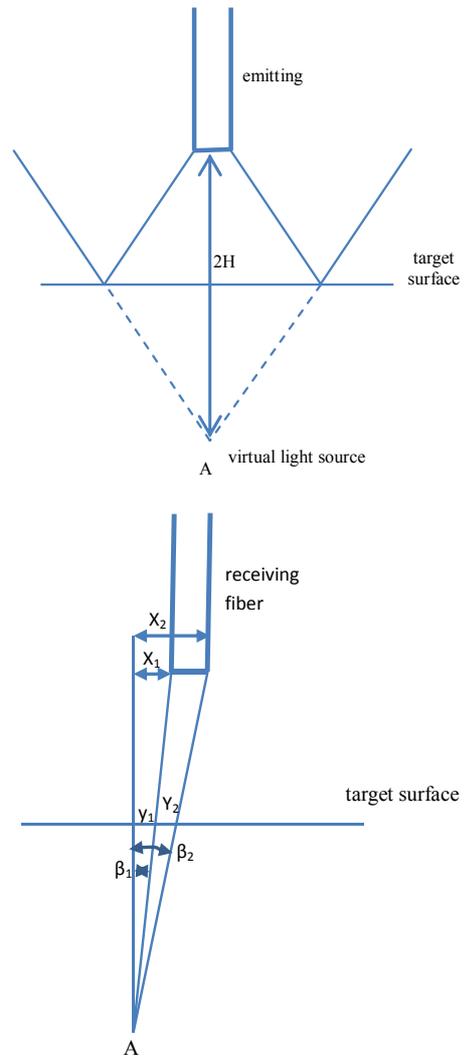
For the fibers used in the present paper the spatial resolution is 150  $\mu\text{m}$  and 300  $\mu\text{m}$  respectively.

#### 4. Error Analysis

The error in measuring the film thickness the can be due



**Figure 4. Calibration curve on the finger without the liquid (solid curve) and with the FC43 (liquid curve).**



**Figure 5. Spatial resolution of the fiber optic probe.**

to the following reasons:

- Error in the perpendicularity of the probe ( $\delta_a$ ). With a deviation of the probe from the perpendicular of 1°

and a stand-off distance of the probe from the film of 1.5 mm results in an error of about 1  $\mu\text{m}$ .

- The error in measuring the zero reading of the distance between the fiber probe and the liquid surface is the minimum graduation on the scale of the micro screw, which is 5  $\mu\text{m}$  ( $\delta_b$ ).
- Error in measuring the stand-off distance from the fin ( $\delta_c$ ); this is the roughness of the fin which is around 5  $\mu\text{m}$ .

The total error can therefore be computed as following [13]:

$$\text{Error} = \sqrt{\delta_a^2 + \delta_b^2 + \delta_c^2} = 7.1 \mu\text{m}$$

## 5. Results and Discussion

Before measurements were carried out the finger (of 18 mm height) was covered by a black coating in order to avoid reflection from its surface. FC43 was poured on the finger with a set flow rate of 5.96 ml/min. Two film thickness measurements were carried out along the finger surface: one towards the top of the finger and one towards the middle of the finger. **Figure 6** shows the measurement at the finger middle point. At both fiber optic locations two measurements were done: one with the dry finger and the second with the wet finger. The first measurement location is near the finger top at a distance of 5.4 mm from the finger top. The second measurement location is near the middle of the finger at a distance of 11.6 mm from the finger top. The fiber optic probe was rotated at the measuring point till the reading showed a maximum, this meant that the probe was orthogonal to the measuring surface.

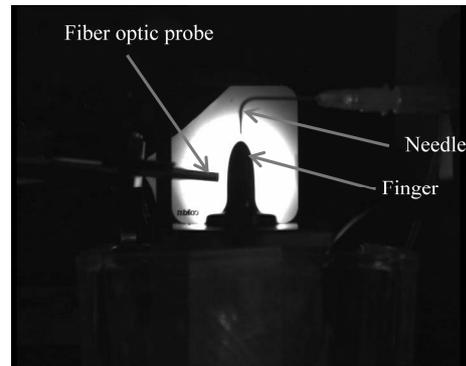
Using the calibration curves a film thickness of 163 microns has been measured near the finger top. A film thickness of 79 microns has been measured in the middle of the finger. The decrease of the film thickness from the top to the middle of the finger is due to the fact that near the top the finger is thinner than in the middle.

One of the limitations of fiber optic measurements for film thickness is the need of an *in-situ* calibration. In fact, the background light influences dramatically the measurements done. Therefore, this technique is not “portable”.

## 6. Conclusions

A fiber optic probe can be used for thickness measurement of the liquid film flowing along a curved surface. A “finger” type surface has been manufactured and a non-volatile liquid (FC-43) has been poured on top whilst film thickness measurements were being done in 2 discrete locations along its height. Film thickness of 163 and 79 microns were measured along the fin surface.

This preliminary work shows that film thickness in the



**Figure 6.** Fiber optic probe measurement on the finger middle section.

region of 100 microns can easily be measured using fiber optic probes.

The fiber optic probe is useful measurement technique for investigation of the liquid film arisen during vapour condensation.

This work is important for condensation of liquids on top of curvilinear surfaces which will be the topic of a further research work.

## 7. Acknowledgements

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