Film Thickness and Wave Velocity Measurement Using Reflected Laser Intensity

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Abstract: *The objective of this work is to develop a film thickness and velocity measurement technique using laser intensity measurement in liquid film flow. This technique was developed for annular flow studies, but it has been scarcely used due to the equipment's complexity, if compared to other techniques. The laser technique uses the reflection of the laser beam in water interface and the attenuation of its intensity to determine the interface position. Thus, the relation between intensity and thickness must be obtained by calibration. A theoretical model was proposed for the optical phenomena present in the film thickness measurement. The numerical results of the model were compared to a simple experiment using a planar mirror. A controlled experiment was made using one-dimensional waves in a short channel where the wave frequencies were varied by changing the vibrator's frequency and the film thickness were modified by changing the liquid volume. The reference film thickness was obtained by the analysis of photographic data taken through the channel transparent walls, allowing the comparison to the results taken by the laser technique. The experimental results for the film thickness presented a good agreement to reference photographic data. The interface wave propagation velocities were measured with a good accuracy, showing good agreement to the theoretical data.*

Keywords*: film thickness, laser, flow, annular, intensity.*

1. Introduction

The instrumentation used to measure film thickness in annular flow usually utilizes conductivity principles that are essentially affected by temperature and concentration of electrolyte. The probes used may cause interference in the measured flow. As the permissivity varies less with temperature than conductivity, the capacitive methods solve those related problems, but capacitive techniques always provide local average values.

Otherwise, ultra sonic techniques, as described in KAMEI; SERIZAWA (1998), are local techniques and are independent from variation of the electrical properties of the working fluid during the experiments. However, the uncertainty associated with this technique is directly related to the wavelength (in this case 75mm). The uncertainty of this technique is high when compared to other techniques.

FUKANO (1998) described a local probe that utilizes constant current technique that provides lower values of the uncertainties but, as already discussed, present the problem of variation in conductivity when temperature varies. This probe also presents limits for the film thickness measurement in such a way that a thickness thinner than the probe electrodes displacement dimensions could not be well measured. There is another limitation for the maximum film thickness that could be measured in terms of probe dimension.

The fluorescence-based techniques, as described in HEWITT *et. al.* (1992), are essentially local techniques and in some cases the fluorescence effect can be stimulated by laser, as described in DRISCOLL *et. al.* (1992). The concentration of fluorescent material must be controlled to avoid its saturation.

Laser beam can be used to measure film thickness using attenuation of intensity due to the absorption by the fluid. SAMENFINK *et. al.* (1996) describes a system that measures film thickness and interface inclination, but despite the possibilities of such technique, it requires that the flow occurs in an open channel to install optical detection equipment in the opposite side of the laser beam source. Thus, this technique cannot be applied to annular flow.

The utilization of laser attenuation is described in OHBA *et. al.* (1992) where the radiation reflected by a gas-liquid interface is measured. The variation in reflected radiation intensity is related to film thickness. The major advantage of this technique is that the flow is not disturbed. The measurement of reflected total flux is made through the same optical fiber that launches the laser to the measurement point. The intensity of the reflected ray that returns by the optical fiber is directed to a photodetector that measures its intensity. This technique only detects the thickness when the interface is parallel to the tip of the optical fiber. When the interface is parallel, the equipment detects a signal peak. This peak is observed only when a peak or a valley of a wave passes over the optical fiber tip.

YU; TSO (1995) proposed to use various optical fibers, one central to launch laser in measurement point and others, equally spaced around it, to detect radiation reflected by the gas-liquid interface. The objective is to overcome the limitation involved in the one fiber probe. As described, the one fiber probe only detects film thickness when the interface is parallel to the optical fiber tip. YU; TSO (1995) concluded that with the new multi fiber probe is not possible to measure inclination of gas-liquid interface, but the probe increases the range of thickness that could be measure by reflected laser intensity technique to 4 mm thickness.

The objective of this work is to develop a film thickness and velocity measurement technique using the laser intensity attenuation principle. A theoretical model is proposed and the numerical results of the model are compared to a simple experiment using a planar mirror. A controlled experiment is conducted using one-dimensional waves in a short channel where the wave frequencies are varied by changing the vibrator's frequency and the film thickness are modified by changing the liquid volume. Analysis of photographic data taken through the channel transparent walls allows the comparison to the results taken by the laser technique. The interface wave propagation velocities are also measured.

2. Description of Technique

The proposed experimental apparatus is sketched in Fig. (1). Optical fibers with 500 μm core diameter are used in the experiment. They presents good installation properties and increase the measurement range if compared to the fibers with core diameter of 50 μm and 80 μm tested by OHBA *et. al.* (1992), without increasing the number of optical fibers.

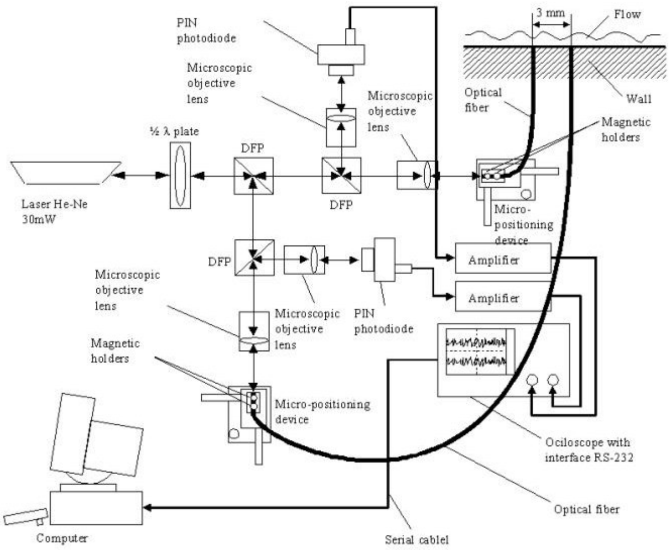
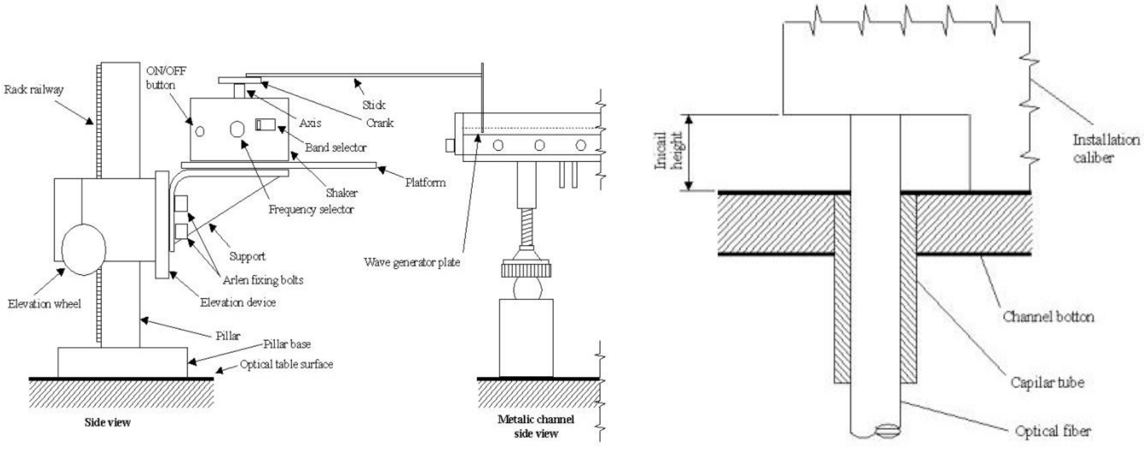


Figure 1. Lay out of optical arrangement used to launch radiation in optical fiber.

In order to launch the laser radiation in the optical fiber and to detect the reflected radiation, an optical arrangement is used to adjust laser radiation properties. As can be seen in Fig. 1, only one laser source is used. By using a beam splitter, the original beam is divided in two. The two emerging beams have their intensity adjusted by a half wave plate placed between the laser and the first beam splitter. Both beams are launched on microscopic lenses that focalize them in the tips of the 500 μm core diameter optical fibers. The optical fibers conduct the radiation to the measurement point. The radiation emerges from the opposite tip of the optical fiber, travels across the water film and reaches the interface. The major part of the radiation is transmitted through the interface, but a small portion reflects back through the water film to the optical fibers. The reflected radiation emerges in the other end of the optical fiber, passes through the microscopic objective lenses, is reflected by the beam splitters to a second microscopic lens that focalize each beam in its respective photoconductive diode PIN.



(a) **(b)**

Figure 2. (a) Arrangement of the wave generator and the schematic view of the channel. (b) A view of optical fiber installation.

The current drained by a PIN photodiode is transformed in voltage signal by two amplifiers that send their signal to an oscilloscope. The oscilloscope has a RS-232 port that can be read by a computer.

The optical fibers are installed in the measurement point with 3 mm distance between them in the wave propagation direction. Thus, the film thickness is measured in the both optical fibers and the resultant signals can be used to calculate the correlation coefficient to determine the wave propagation velocity.

A wave generator was built to generate one-dimensional waves in order to create an appropriate measurement condition. Due to the channel dimensions and the surface tension of water the waves reflections were considered negligible and no caution was taken with respect to this disturbance. The wave generator was built using a step motor that was activated by a transistors bank connected to a logical sequencer. The frequency was controlled by a clock generator microchip. The clock frequency depends on an external resistor that, in this case, was a potentiometer. The axis of the step motor was connected to a crank, which transmits the vibration to the wave generator plate. The wave generator was installed over an adjustable level platform in order to allow a good positioning with respect to the channel position.

The schematic view of the optical fiber installation in the measurement location as well the channel and the wave generator can be seen in Fig. (2). The fibers are placed with a known distance from the channel bottom to avoid interference due surface tensile effects. The formation of meniscus can lead to a false thickness measurement. The photograph in Fig. (3) shows the generated one-dimensional waves traveling through the channel.

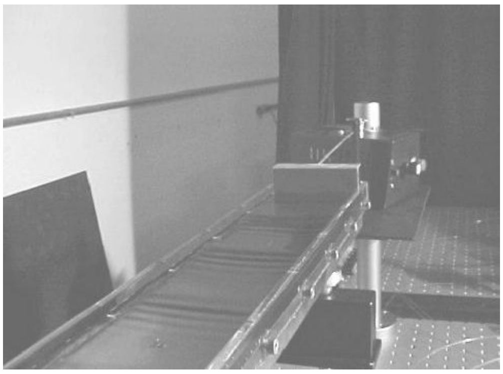


Figure 3. Waves traveling through the channel.

In order to have a reference thickness value, pictures of the film at the measurement point were taken to compare with measured results. The scheme of Fig. (4) shows the camera installation at the side of the test channel. The walls of the test channel were built of acrylic material to allow visualization of flow through the walls. A device was used to amplify the local image of the optical fiber.

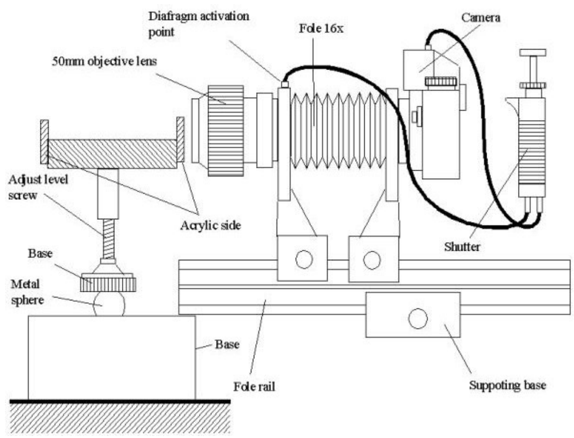


Figure 4. Installation of photographic camera in the side of test channel.

3. Numerical Modeling

The total flux detected by the optical system can be calculated by intensity integration using mirror symmetry principles. The intensity can be integrated over the area of the optical fiber tip image. By knowing the position of the interface (distance and inclination), it is possible to determine the position of the image using symmetry principles. The integration of the laser flux radiation that passes through the area was based on the position of the tip image in space. Figure (5) shows the position of the image.

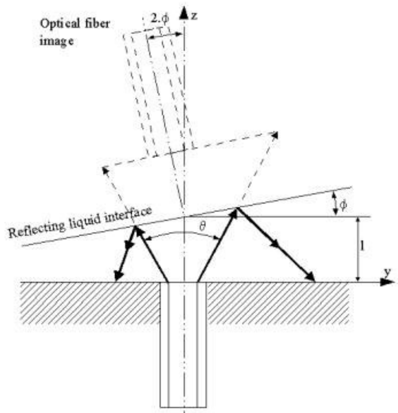


Figure 5. Position of optical fiber image obtained by symmetry principles.

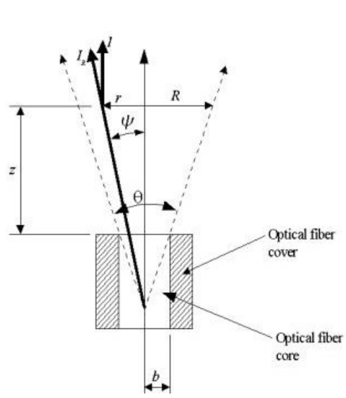


Figure 6. Schematic drawing that shows the radiation components as well the angles involved in the integration of the intensity flux.

The intensity flux distribution of a laser beam follows a Gaussian distribution curve. The equation that describes this curve is given below:

$$I(r,z) = I_{CL}(z) \cdot e^{-\frac{4 \cdot r^2}{R(z)^2}} \qquad (1)$$

in which z is the vertical coordinate in the direction of the optical fiber axis, *R(z)* is the radius of the beam, r is the radial coordinate (perpendicular to the optical fiber axis direction), *ICL(z)* is the flux intensity in the center of laser beam and *I(r, z)* is the local intensity inside the laser beam. The laser beam that emerges from the optical fiber has the same distribution curve.

The flux in the center of the laser beam *ICL(z)* is given by:

$$I_{CL}(z) = \frac{4 \cdot I_0}{\pi \cdot R(z)^2 \cdot \left(1 - e^{-4}\right)} \qquad (2)$$

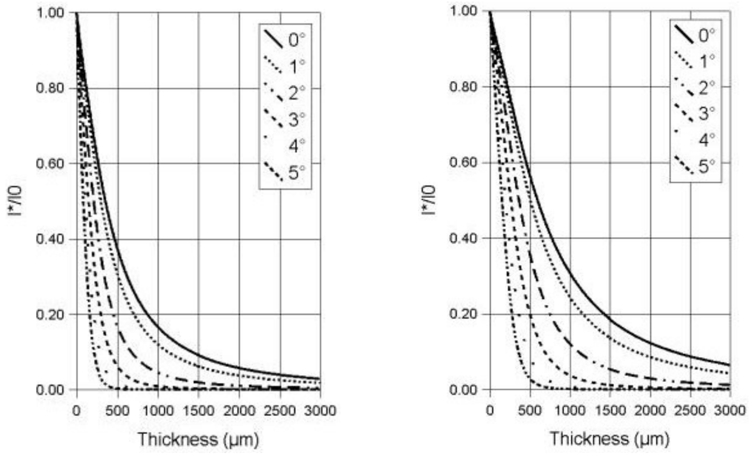
in which I_0 is the total flux that pass through the radiation emitting device or the tip of the optical fiber. Figure (6) shows a schematic view of the symmetry-modeled situation. It can be seen the angles and the radiation components to be used to calculate the radiation over the optical fiber image position.

The flux $I_r(r,z)$ can be obtained through some algebraic steps as:

$$I_r(r,z) = \frac{4 \cdot I_0 \cdot e^{-\frac{4 \cdot r^2}{R(z)^2}}}{\pi \cdot R(z)^2 \cdot \left(1 - e^{-4}\right)} \cdot \sqrt{1 + \left(\frac{r}{R(z)^2} \cdot \tan\left(\frac{\theta}{2}\right)\right)^2} \qquad (3)$$

The integration of the intensity flux over the optical fiber tip image gives the total flux passing through the image. This is an ideal situation, but it can be measured using a plane mirror put in front of the optical fiber. This very simple experiment can give a confirmation of this numerical simulation.

OHBA *et. al.* (1992) used two optical fibers with 50 μm and 80 μm core diameter. The numerical results for these diameters are shown in Fig. (7).



(a) (b)

Figure 7. Numerical results for optical fiber with 0.2 numerical aperture and 5.28° beam emerging angle according OHBA *et. al.* (1992). (a) 50 µm and (b) 80 µm core diameter.

The acrylic optical fiber used in this study has 0.5 numerical aperture, 500 µm core diameter and the emerging beam has 23.16°. The numerical results for this optical fiber are shown in Fig. (8).

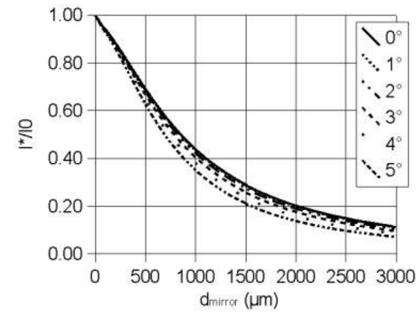
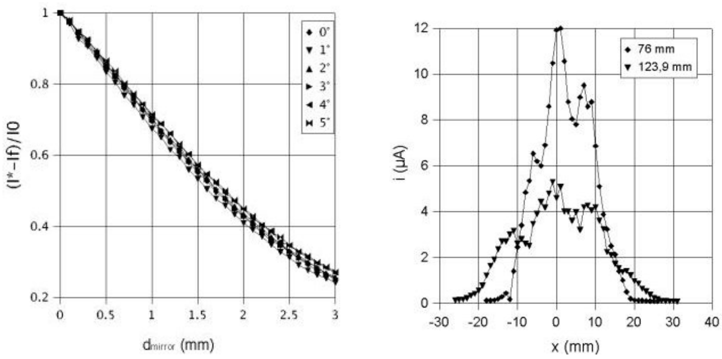


Figure 8. Numerical result for optical fiber with 0.5 numerical aperture, 500 µm core diameter and the emerging beam has 23.16°.

4. Results and Discussions

A single experiment with a planar mirror was performed in order to verify the behavior described in Fig. (8). The discrepancy between numerical results and measured points can be explained by observing the intensity distribution in the emerging beam. This distribution was measured and was not exactly as supposed in the numerical model. Due to imperfections inside the optical fiber, a perfect Gauss distribution shape was not observed, as seen in Fig. (9b).



(a) (b)

Figure 9. (a) Results of planar mirror experiment with 500 µm acrylic optical fiber. (b) Flux intensity profile of the laser beam in two distances from emitting lens.

The difference between the theoretical and the measured intensity results can be explained by the characteristics of the acrylic optical fibers that have great internal attenuation when compared to glass optical fibers. Another significant problem is the fragility of this fiber that accumulates failures when manipulated. These internal failures contribute to the departure of measured intensity profile from the Gauss distribution profile. The internal failures also cause radiation leakage that can be observed by inspection of the optical fiber when it is conducting light radiation.

The calibration of the optical system was made using the same test channel. The signal to thickness relation was obtained by adding discrete quantities of known water volume in the channel and recording the signal in the computer. The curve obtained with this process was used to translate the data recorded in the experiment to film thickness.

The experiment was based on the variation of the film thickness and the wave frequency. It was added to the channel a known volume of water that corresponded to an average thickness. Then the signal for three frequencies selected in the wave generator was measured. One photograph for each frequency was taken. Then, it was added more water to the channel and additional data were taken for three frequencies as well as the respective photos. These measurements were done for three additional levels in order to verify the behavior of the technique under different frequency and film thickness variations.

The measured signals were filtered by the application of an averaging filter. The resulting curves were filtered again by a algorithm that looks for peaks and valleys, once this technique gives only this type of information. Then, the resulting filtered points were translated to a thickness signal using the calibration curve. Figure (11) shows a typical curve obtained by using the described procedure.

These results were compared to the photographic results and showed good agreement in terms of order of magnitude. The photographic process did not generate enough data to allow a precise comparison. Each photographic image, when processed, revealed only a small part of the curve shown in Fig. (11). Sometimes the photos did not have peaks or valleys to be compared to the results of the laser technique. These results were also compared to the average volume and showed a good agreement.

The photos were taken with a device, shown in Fig. (4), that amplifies the image size depending on the adjusted distance between the objective lens and the camera. This device not only amplifies the image size, but also reduces the light intensity needed to take pictures. As the image was amplified, less light intensity remained to impress the photographic film. Therefore, for large amplifications, it was necessary to use high sensible photographic films. However, cheaper photographic films can be used if a good illumination to the object was provided. The pictures were taken by using a special scheme of illumination for the liquid film. One example of the pictures taken from optical fiber installed in the channel can be observed in Fig. (10). The gas-liquid interface can be observed in this picture.

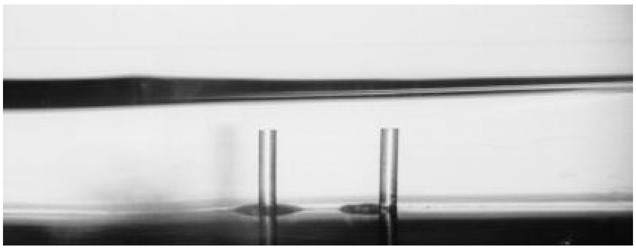


Figure 10. Picture taken from the place where the optical fiber were installed. The height of each optical fiber is 3 mm (from bottom of the channel to optical fiber tip).

The measurements of interface velocity and frequency were made using the calculation of correlation coefficient between the two signals recorded from each oscilloscope channel (each channel connected to one optical fiber). After application of the averaging filter, the signals were used to calculate the interface wave velocity and frequency. The results for each average thickness can be observed in Fig. (12). The wave velocity calculation was conducted by using evaluating the correlation factor. Once the oscilloscope signal is an array of discrete points, by the introduction of a given delay between signals for a given interval of sample units and calculating the correlation, it shall exists a given interval of time samples that maximize the value of correlation. By dividing the distance between the optical fibers by the obtained time interval, it was possible to calculate the wave velocity.

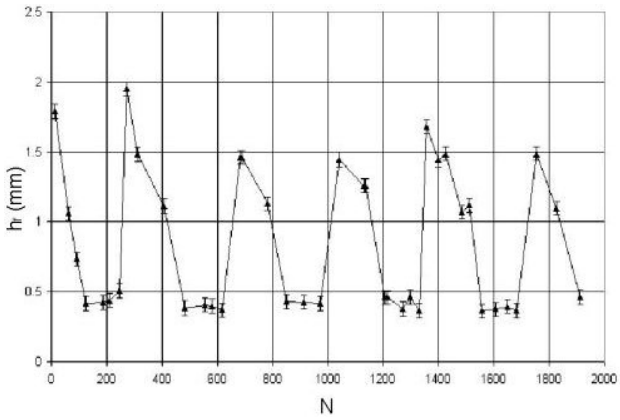


Figure 11. Peaks and valleys filtered from the original signal translated to thickness information by using calibration data.

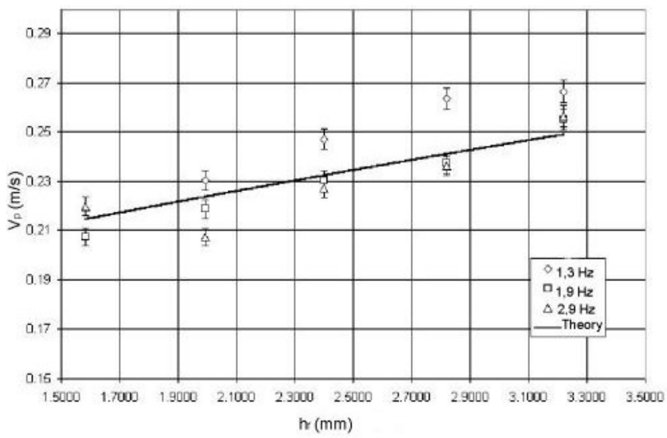


Figure 12. Wave velocity for each average thickness and frequency compared with theoretical data.

The same can be done for frequency calculation, once the proposed wave generator creates a periodic perturbation in the gas-liquid interface. Then, the maximization for the correlation coefficient will be found twice, once for the delay between the signal passing through the two optical fibers and another for one entire wave period.

The theoretical values for velocity for each thickness can be obtained by the following equation:

$$v = \sqrt{h \cdot g} \qquad (4)$$

where *h* is the film thickness and g is the local gravity acceleration.

The obtained velocity was compared to the theoretical values and showed good agreement, despite some small deviations. The deviations found is due to the assumptions adopted during the deduction of the theoretical equation that calculates the wave velocity.

For the film thickness measurement, the uncertainties were evaluated by combination of the uncertainties of the various measurement devices. However, during the calibration process, the uncertainty of the oscilloscope signal was obtained by calculation of the standard deviation. To calculate the expanded uncertainty, it was used a factor of two for 97,73% confidence (two standard deviation). The overall uncertainty for the presented film thickness measurement technique was calculated and is 0.22 mm. The uncertainty of the velocity was calculated by combination of the available measurement devices and was found a value of 0.01 m/s.

5. Conclusion

The objective of the present work was to develop a film thickness and velocity measurement technique using laser intensity measurement in liquid film flow. This work, which comprises both theoretical and experimental studies, was successfully conducted and provided important results.

The utilization of optical fibers with big core diameters increased the measurement range (up to 4 mm) and allowed great installation tolerances, when compared to small core diameter fibers. For this type of optical fiber the angular errors in installation are acceptable and do not cause any relevant effect on the quality of measurements.

A theoretical model was proposed for the optical phenomena present in the film thickness measurement. The numerical results of the model were compared to a simple experiment using a planar mirror. The overall calculation procedure was proved to be valid, although differences between theoretical and experimental results were found. These differences were caused by the use of acrylic fibers that introduced distortions in the beam intensity distribution. The acrylic optical fiber with 500 μm was less tolerant to manipulation, causing accumulation of damages in the fiber. These damages caused deviations in the intensity distribution of the beam that emerges from the optical fiber.

A controlled experiment was conducted with one-dimensional waves in a short channel. The wave frequency was varied by changing the vibrator's frequency and the film thickness was modified by changing the liquid volume. The reference film thickness was obtained by the analysis of photographic data taken through the channel transparent walls, allowing the comparison to the results taken by the laser technique. The experimental results for the film thickness presented a good agreement to reference photographic data. The interface wave propagation velocities were measured with a good accuracy, showing good agreement to the theoretical data. These results showed that the velocity was not influenced by the frequency but only by the thickness of the liquid as foreseen by the theory.

6. References

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