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AN INTRUSIVE METHOD FOR FILM THICKNESS MEASUREMENT ON SMOOTH HORIZONTAL TUBES FOR SUBCOOLED WATER

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ABSTRACT

Falling film evaporation technique is widely used in different applications such as in heat exchangers in desalination devices, absorption/desorption-type chillers, OTEC (ocean thermal energy conversion primer), petrochemical, and chemical process industries, just to mention a few industries. However, in spite of numerous studies the complete understanding is not totally clear yet, even some basic phenomena such as the behavior the film thickness and its relationship with the heat and mass transfer coefficients. The objective of the present work is present the study of an intrusive method for measuring a descending film thickness employing subcooled water as the working fluid at atmospheric conditions. The method used a novel configuration (leverage effect) in which a micrometer reading has its precision improved. As a needle tip touches the liquid film, an electrical current flows in signalizing the tip position and, consequently, the film thickness. The current proposal presents an accuracy 22% when compared with the theoretical result of Nusselt.

INTRODUCTION

Heat transfer through falling film evaporation is an important and commonly used process. It has been widely employed in heat exchangers in desalination devices, absorption/desorption-type chillers, OTEC (ocean thermal energy conversion primer), petrochemical, and chemical process industries, just to mention a few industries.

One of the most prominent characteristics of falling film evaporation technology is the low refrigerant charge, which is an attractive feature in the refrigeration industry because of the high costs of HFCs and HCFCs or because of the objective of increased safety in the case of ammonia [1].

OTEC pilot plants using this technology to achieve a close temperature approach between the evaporating fluid and the heating fluid, and hence a higher cycle thermal efficiency [2]. Falling film evaporators have been used extensively in chemical processing plants due to their minimal fluid residence time and high heat transfer rates with low temperature differences [3]. That advantage is used by the industry food because there are products thermo-sensible.

Falling film evaporators have the following advantages concerning to flooded evaporators: (1) avoid the elevation of the boiling temperature caused by hydrostatic head in the lower part of evaporator. This effect is important in evaporators of large vertical dimensions, (2) high heat transfer coefficient, which improves the cycle efficiency, (3) low temperature difference between the fluid and the heated surface. It helps to utilize low-grade waste heat and avoids the superheating at the surface tube, increasing de energy efficiency of the system, (4) minimal pressure drop. This is important when the working fluid is a viscous liquid one as it is often the case of petrochemical and chemical process industries, (5) minimize the refrigerant charge, capital e operating costs, [1,2] and, (6) mitigate fouling and non-condensable effects [4].

In falling film evaporation processes, the working fluid is distributed by a distributor tube or spray nozzle over the tube top, forming a thin film of liquid around the tube. The present article provides a novel method to measure the film thickness formed on the external surface of the tube, which use an alternative device to register the indirectly film thickness.

NOMENCLATURE

g	[m/ s^2]	Acceleration of gravity
L	[m]	Length
$\dot{m}$	[kg/ s]	Mass flow rate
Re	[-]	Reynolds number

Special characters

$\theta_{contact}$	[°]	Contact angle between the fluid and the surface
ρ	[kg/m^3]	Density
μ	[Ns/ m^2]	Dynamic viscosity
Γ	[Kg/ ms]	Mass flow rate per unity of length - each side
δ	[m]	Film thickness

Subscripts

i	Inlet
l	Liquid
v	Vapor

EXPERIMENTAL SETUP

An overview of the test rig for measuring falling film thickness is presented next. Other main components such as the distributor are also discussed due to the importance to guarantee a good distribution around the testing tube surface.

Test Rig

The study of film thickness in falling film technology was carried out using the test rig depicted in Figure 1. The positive displacement pump circulates the working fluid to the water storage tank, which is used to guarantee the continuous flow through the distribution system. Posteriorly, in the piping it was installed a rotameter to register the volumetric flow going to the system. The water level control is used as a mechanism to improve the distribution, so that, the installation of the overflow piping helps to keep the same hydrostatic head pressure on the system. The needle valves installed before of the distribution system were installed for adjusting the mass flow rate in both directions.

The distribution system was based at the arrangement of Ruan et al, 2008 [4], but several alternatives were tested to improve the current configuration, which will be discussed in next section. Once, the working fluid flows in the test section it is collected and stored in the storage tank. Then, it is pumped back to the pre-heating storage tank on the top.

In reference to the film thickness measurement system, the study used an intrusive method with a new configuration (leverage effect) to improve the precision, based on micrometer it was possible to detect the liquid-vapor interface and register the film thickness. The configuration used is shown in Figure 2. The main displacement (vertical direction) is given by the micrometer, transferring the movement until the needle. This new configuration has the clear advantage in comparison with a directly measurement due to multiplicative effect caused by the leverage effect.

For the detection of the liquid-vapor interface it was employed a simple electronic circuit that can detect electrical continuity between the needle tip and the liquid film. Thus, when the needle contacted the film it closed the circuit and, the vapor-liquid interface was registered by the micrometer reading. Also, a given reading was later verified using a zoom in image taken on the contact between the film and the needle.

By the current design of the measurement set up, it can be employed to register values of film thickness at vertical and horizontal configurations. Thus, the values have been taking in different positions and for two horizontal tubes.

Flow Distributor

The distributor system is an important component in falling film heat transfer process because it should be designed to uniformly distribute the flow around the first row tube. If a mal distribution happens on the first tube, the others tubes, below it, will have also a mal flow distribution problem as well.

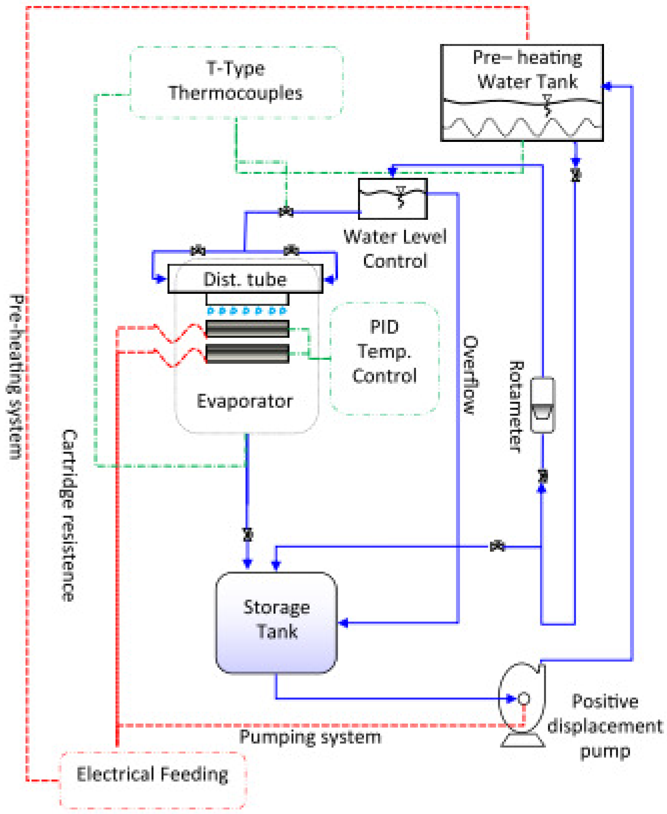

Figure 1 *Schematic representation of the falling film evaporation test rig.*

The distributor have to wet all the surface of the first tube and its height must be appropriated. Yang and Shen [5] observed that the liquid feeder height could affect the heat transfer coefficient because the fluid will gain slightly more velocity, this increase in velocity over the heating tubes helps to enhance the heat transfer. When the fluid reaches higher velocity, the convective heat transfer increases and this allows the heat exchanger to run efficiently. However, raising the distance too high can result in an ineffective fluid covering of the heating tubes (dryout), yielding to a low heat transfer coefficient. They concluded that there is a maximum height above which there are many dry spots on the tube, in its work, they pointed out as 11 mm but this value depend of the mass flow. It is possible that for high height the liquid flowing down from the distributor creates little drops spilling out the tube. In such situations, of course the heat transfer gets worse.

According Chyu and Bergles [6] in nonboiling and turbulent condition the heat transfer coefficient is slightly affected by the feeder height. However, the heat transfer coefficient is less sensitive to the change in liquid feed height for low Reynolds number.

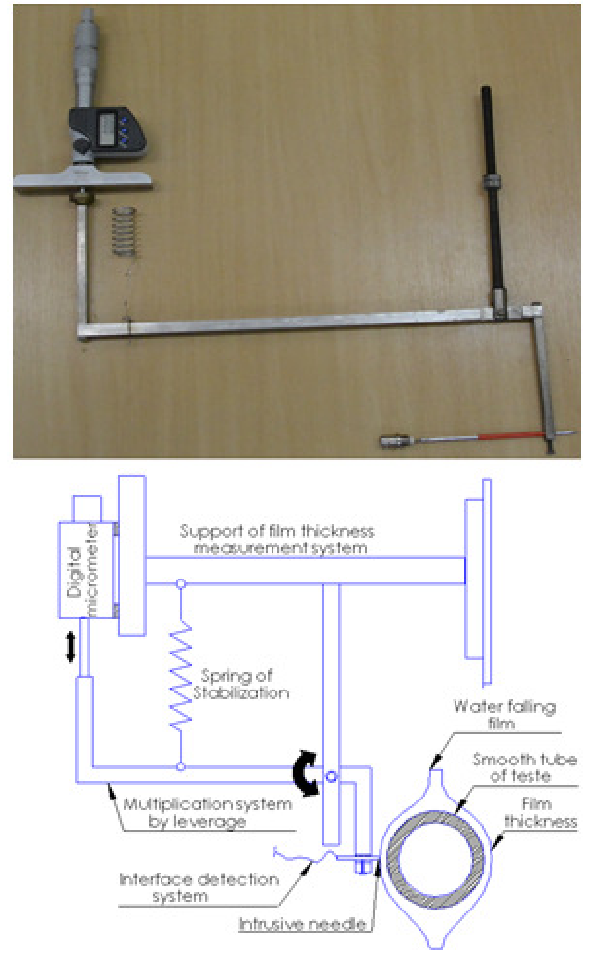

Figure 2 *Schematic representation of the film thickness measurement system. As the needle touches the film an electrical current is established (not shown in the illustration).*

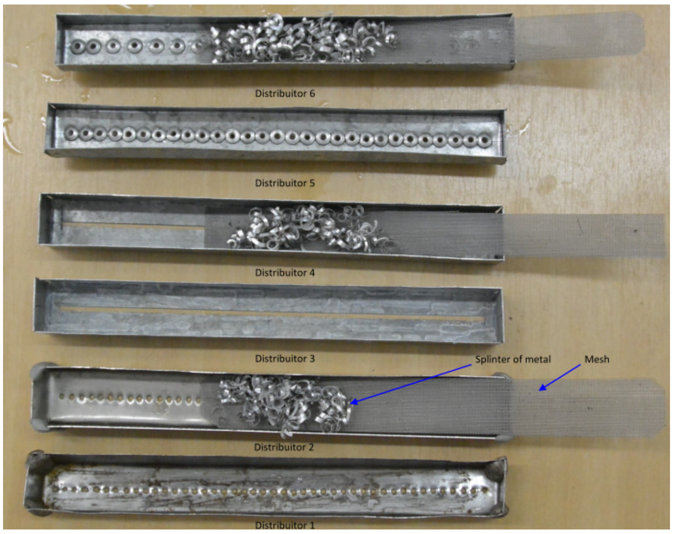

Figure 3 *Types of flow distributors tested.*

Parken et al [7] compared two distributors, the first one was a perforated plate (the same used by Fletcher et al [8]) and the other one was a thin-slot distributor. He found that for similar conditions the former gave higher heat transfer coefficient. Therefore, the perforated plated can offer a thinner liquid film than the thin slot distributor, maybe because the liquid going down brakes the boundary layer next to it. In this work, several distributors were test as shown in Figure 3. It was possible to seen in that figure that there are three configurations of plates: with holes (distributor 1 and 2), with groves (distributor 3 and 4) and with nozzles (distributor 5 and 6). Additionally it is important to feed and keep the liquid inside the distributor evenly, so it was tested to three different ways to do this. The experimental results of those distributors are presented in Figure 4.

Film thickness calculate

Nusselt [8] introduced a theoretical method to calculate the film thickness in falling films, given by Eq. (1).

$$\delta = \left[\frac{3\mu\Gamma}{\rho_l(\rho_l - \rho_v) g Sin\theta_{contact}} \right]^{1/3}, \qquad (1)$$

where, the mass flow rate per unit of tube length on each side of the tube is:

$$\Gamma = \frac{\dot{m}}{2L} \qquad (2)$$

The film thickness of Nusselt is only applicable to the laminar regime and, this will not compute the crests formed over the tube.

To calculate the Reynolds number it was used the proper definition of the Reynolds number, given by Eq. (3).

$$\mathrm{Re} = \frac{4\Gamma}{\mu} \qquad (3)$$

Instrumentation

For the directly film thickness measurement it was used a micrometer with a one micron accuracy. The study used T-Type thermocouples for temperature measurements. In addition, It was used a rotameter for flow measurements, thus the measurements of volumetric flow were verified with a scale of 0,01 of precision. Finally, the temperature control was done with a PID controller with a 0,1°C of accuracy.

Test procedure

In order to validate of the film thickness measurement method it was fixed the temperature of the working fluid and the Reynolds number in a specific point in the laminar regime. The system has two smooth tubes, which were used to measure the film thickness in each tube side.

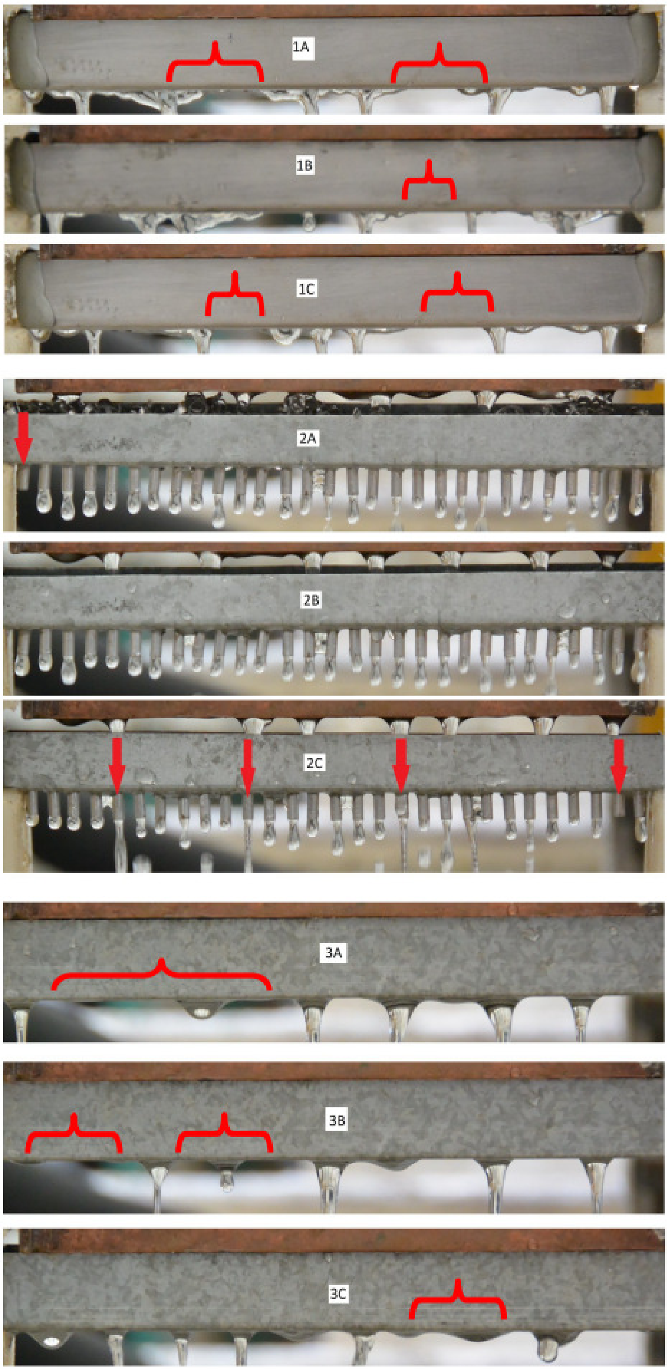

Figure 4 *Comparison of distributors in falling film evaporation (Re=1100, 1a,b,c-distributors 1 and 2; 2a,b,c-distributors 2 and 4; 3a,b,c-distributors 5 and 6).*

For the film thickness, measurement was adopted the following order:
First step: the needle does not touch the film. Then the "zero" value is initialized when the needle is in contact with the interface. First evaluation of film thickness (δ_1) is obtained when the needle reaches the tube surface.
Second step: the needle is pulled back from its current position (in contact with the tube surface) to the liquid-vapor interface. The second evaluation of the film thickness (δ_2) takes into account the surface tension ($\delta_2 > \delta_1$). For this step, the liquid-vapor interface is registered as soon as the film breaks up its contact with the needle. At this instant, the needle displacement is stopped. A sequence of still pictures showing the influence of the surface tension is shown in Figure 5.
Third step: the needle is pushed again in direction of the film interface until the contact is done once again. The distance that separates the previous position until the interface (δ_2 - δ_3) represents the surface tension effects occurring during the needle intrusion.

Transport properties and operational conditions

In order to validate of the film thickness measurement method it was fixed the Reynolds number, measuring various times the film thickness in different axial positions of each one side. Table 1 presents a summary of relevant transport properties and operational conditions.

Table 1 *Transport properties and operational conditions.*

Variable	Value
Reynolds, Re [-]	1105
Temperature, T [°C]	95
Liquid density, ρ_L [kg/m^3]	965,3
Vapor density, ρ_V [kg/m^3]	0,5545
Nusselt theoretical film thickness, δ [mm]	0,2078
Gravity acceleration, g [m/s^2]	9,81
Film angle from top, Θ [°]	90
Dynamic viscosity. μ [kg/s.m]	0,000315
Mass flow per length unity, Γ [kg/s.m]	0,08689
Total mass flow, $\dot{m}$ [kg/s]	0,03128

RESULTS

The results obtained of the film thickness measurement are presented in Table 2.

Table 2 *Main results of the film thickness measurement.*

	δ_1	δ_2	δ_3
Film thickness measured -Averaged [µm]	285,6	696,2	266,4
Film thickness by Nusselt computation, Eq.(1) [µm]	207,8	207,8	207,8
Absolute difference [µm]	77,8	488,4	58,6
Relative deviation (%)	27,24	70,15	22,00

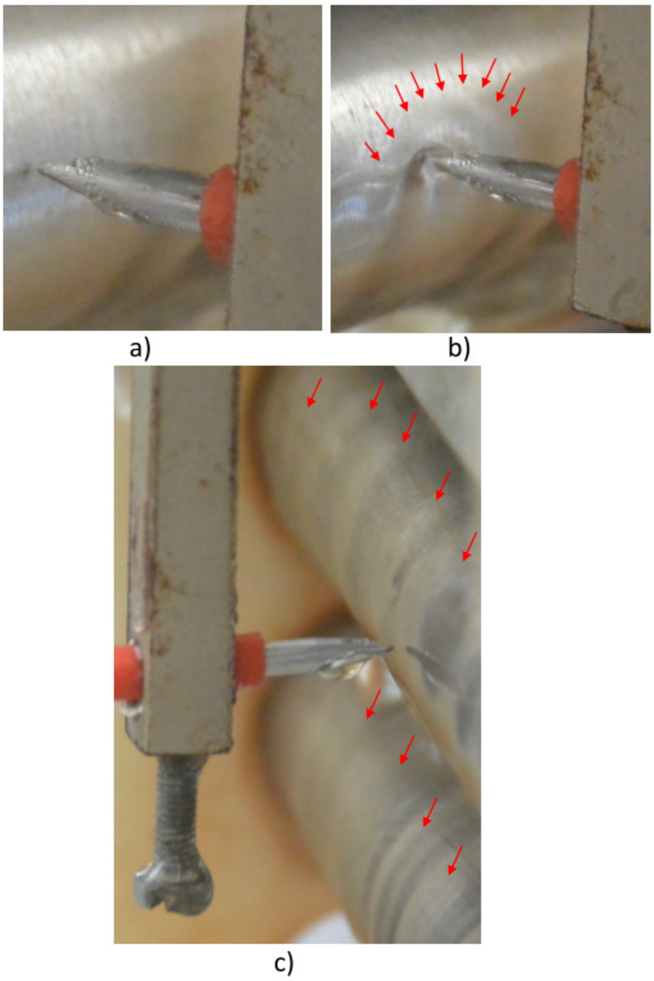

Figure 5 *Still pictures showing the needle a) without contacting the liquid film, b) contacting the liquid film and, b) crest detection (wavy regime).*

DISCUSSION AND CONCLUSIONS

In this work, an intrusive method to measure the film thickness in falling film on a horizontal tube was analyzed. It was noticed that the distributor is a critical device in falling film process because the uniformity of the liquid film on the tube and the heat transfer process depends of that. Three kinds of measurement of the film thickness are possible, one when the tip touches the liquid film and goes on to touch the tube metal surface, the second when the tip moves out from the liquid and the other one when the tip is pushed against the liquid film. It was observed the last one gives the best approximation (22%) to the theoretical Nusselt thickness. The technique has shown some limitations because the surface tension locally disturbs the liquid film that can induce to some erroneous film thickness readings. In addition, wavy film regime may mislead the results and one need to properly address this point. However, a dominating wavy frequency can be obtained if the electrical signal generated due to the needle-film contact is recorded by a data acquisition system and analyzed by FFT software.

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