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ABSTRACT

The performance of heat transfer in the processes of evaporation, absorption, distillation and even condensation is affected from the wetting behavior of the liquid film flow on the surface. The complete wetting of the surface is usually required while breaking of thin liquid film is to be avoided. Various experimental settings have been designed by several researchers to investigate the main parameters influencing the stability of the film. However, in order to generalize and properly scale the results, the appropriate dimension of the test section and its influences on the wetting behavior are still unresolved questions that need to be addressed. Three different fluid distribution widths, including 200, 100 and 33 mm, when the geometry of distribution hole, the distance between holes and vertical flat surface are fixed, are carried out. Pure water at ambient temperature is used as working fluid. The measurement is focused on the wettability hysteresis and the shape transition from film to rivulet when the water flow rate are increased or decreased for wetting and dewetting experiments. Visual data captured on the test section under various fluid distribution widths are collected and analyzed using image binarization method to quantify the wetted area. The relation between the wetted area with respect to film Reynolds number and Weber number respectively are presented. The results show that the fluid distribution width can influence the wetting ability. The amount of wetted area, which is used to identify the wetting ability, is quite stable for decreasing flow rates, thus delineating the hysteresis characteristics of the wetting behavior of this solid-liquid pair. In general, a longer distributor width seems to be associated to a lower wetting ability and a lower wetting hysteresis. However, the same observation could not be applied to the results extracted with a 33mm width.

1. INTRODUCTION

The heat transfer rate in a falling film heat exchanger can be enhanced by improving the wetting behavior of the liquid film flow on the surface. A fully wet exchange surface is beneficial while the film rupture should be avoided. Although several among the relevant parameters to maintain the stability of liquid film, such as film thickness, mode of fluid distribution, wetted coverage, the transition phenomena between film and rivulet flows, the solid surface treatment, the geometry of the test section, liquid flow rate and fluid properties have been previously investigated, a general agreement on their effect has not yet been achieved.

The film thickness, which is presented in term of average film thickness, is one of the most influential parameter investigated by Portalski et al. (1963), Salazar et al. (1978), Roy et al. (1988), Moran et al. (2002), Kang et al. (2007)

and Lu et al. (2016). The pioneering work of Nusselt (1916) has developed the thin film thickness model (δ) as presented in Eq.(1), from the experimental results of a vertical flat plate under the assumptions of laminar flow under the gravitational force, uniform temperature distribution on the plate surface and constant liquid properties.

$$\delta = \left(\frac{3\,\mathrm{Re}_F\, \mu^2}{\rho^2 g} \right)^{1/3} \tag{1}$$

In Eq.(1) Re_F represents the film Reynolds number, μ and ρ are the dynamic viscosity and the density of the liquid, and g is gravitational acceleration. However, when using Nusselt model for calculating the film thickness, δ is assumed to be uniform along the width of the test section. If the liquid film exhibits a non-uniform distribution, this can affect the calculation of the heat transfer rate leaning to either its underestimation or overestimation.

The literature on falling film experimental studies over vertical and inclined surfaces is concerned with the design of the distributor feeding liquid at the top of the plate and flowing down by gravitation force. The effect of parameters including liquid properties, the geometry and arrangement of the distribution system, the material and surface treatment of test section are addressed when investigating the film thickness, film distribution, minimum wetted rate, and wetted area. Besides experimental approaches, the film wetting behavior has also been studied with reference to numerical results from the approximation of the liquid film mass continuity and momentum equations in 2-dimensions (Meredith K.V. et al., 2011). However, the dimensions of the test section and the distribution systems are selected and designed with substantially different characteristics. Salazar et al. (1978) set the experiment to study the film thickness on a vertical Plexiglas plate of 0.35m in width and 1.55m in length by using distilled water at 24°C as working fluid. Lu C. et al. (2016) investigated the water film thickness and the wavy characteristics of the film on an inclined flat Plexiglas plate of 0.3m in width and 0.8m in length. Lu Y. et al. (2016) has comparatively studied the influences of two distributor-hole geometries on the wetting behavior over a single flat plate surface. The test section was made of stainless steel with the dimensions of 0.4m x 1.0m. Moran K. et al. (2002) conducted the experiment on an inclined copper plate of 0.08m x 1.9m, to investigate instantaneous film thickness and velocity profile in a viscous liquid of 20cS silicone oil. Therefore, the influences of the dimensions of the test section, the width and hole-geometry of the distributor have not yet been clarified and have raised questions about their effect on the wetting behavior. In order to generalize, analyze and properly scale the results, the appropriate assessment of the test section dimensions and distributor geometry needs to be addressed. This study investigates the wetting ability of pure water flow over a vertical flat aluminum surface for three different widths of distributor, including 200, 100 and 33mm, under the same geometry and fixed distance of the distribution holes. Visual images of the experimental test section captured when increasing and decreasing the water flowrate are analyzed by image processing to measure the wetted area and qualitatively describe the flow hydrodynamics for the three different distributor widths.

2. EXPERIMENTAL SETUP

The experimental apparatus hereby describe has been designed to capture the steady state wetted area of a uniform flow distribution on vertical flat surface. Aluminum has been used as the material of the flat plate attached on acrylic vertical wall. The dimensions of the test section plate are fixed: width of 200mm and length of 400mm; the set of three different distributor widths consisted of 200, 100 and 33mm. The geometrical features of the test section and distributor are listed as in Table 1.

Table 1 Experimental conditions

Liquid	-	Water
Temperature	°C	30
Distributor width	mm	33, 100, 200
Geometry of distributor		
Depth	mm	0.5
Hole width	mm	2
Pitch	mm	3.5
Number of distributors	number	9, 29, 57

The geometry of distributor hole is fixed at the depth of 0.5mm, the width of 2mm and the pitch between centers of the holes of 3.5mm. A buffer tank is installed at the top of test section to provide uniform liquid distribution to the test section as shown in Figure 1. A liquid reservoir is placed at the bottom to collect the working fluid and deliver it to the distributor via the circulation pump. The water flowrate is measured by the flowmeter KEYENCE Model FD-SS20A. Although changing in a narrow range, the inlet and outlet water temperatures are continuously recorded during the experiment to assess the change of water properties for the data reduction. Increasing and decreasing the flowrate for recreating wetting and dewetting conditions are performed to observe on the wettability hysteresis phenomenon and the shape transition from film to rivulet via quantitative visual data captured on the test section and image processing.

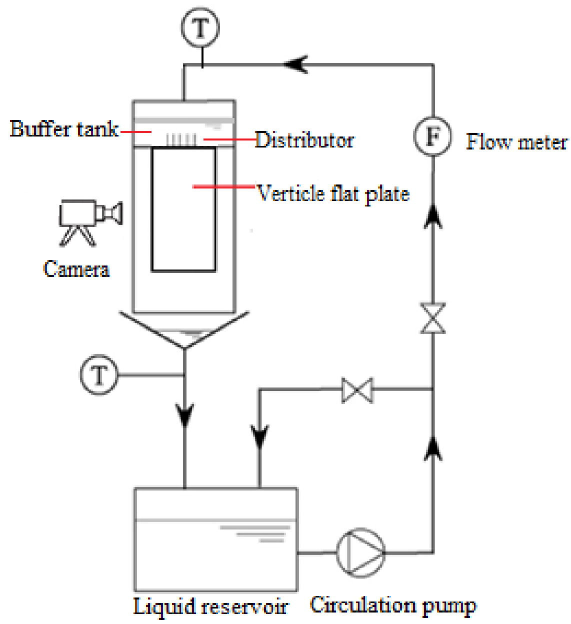

Figure 1: Diagram of the experiment system

In this study, the results are presented in term of wetted area and wetted area ratio (WR) against dimensionless numbers, namely, Film Reynolds number and Weber number which are used to characterize fluid film flow. Film Reynolds number is defined as the effect of liquid inertia relative to its viscosity while Weber number measured the importance of fluid inertial and its surface tension which are respectively defined in Eqs. (2) - (3):

$$Re_F = \frac{4\dot{m}}{b\mu} = \frac{4\Gamma}{\mu} \tag{2}$$

$$We = \frac{\sigma}{\rho \bar{u}^2 \delta} \tag{3}$$

where Γ is defined as the specific liquid load which represents the ratio of the liquid mass flowrate ($\dot{m}$) per unit width of the distributor (b), the Nusselt film average velocity $\bar{u}$ and the film thickness δ.

3. RESUTLS AND DISCUSSION

An image-processing method is introduced in this work to evaluate and quantify the wetted area as proportional to the number of black pixels corresponding to the surface that sees flowing liquid, as compared to the area delineated by the distributor's width and the total length of the aluminum surface. Figure 2 presents the steps of the image processing method. Firstly, the contour of the liquid interface cutting the solid surface is identified and traced (Figure 2b); subsequently, the dry area is cropped out and substituted by white pixels (Figure 2c); finally, the wetted area is filled with black pixels (Figure 2d) and compared to the total area defined by the distributor width and the test section length (dashed contour in Figure 2d).

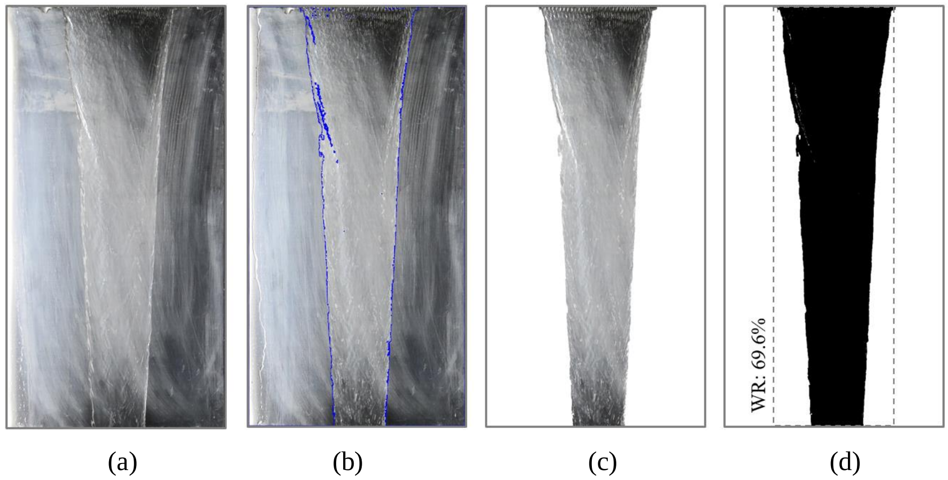

Figure 2: Image processing method: (a) trimmed original image, (b) wetted area contours, (c) reduction to binary image, (d) final image

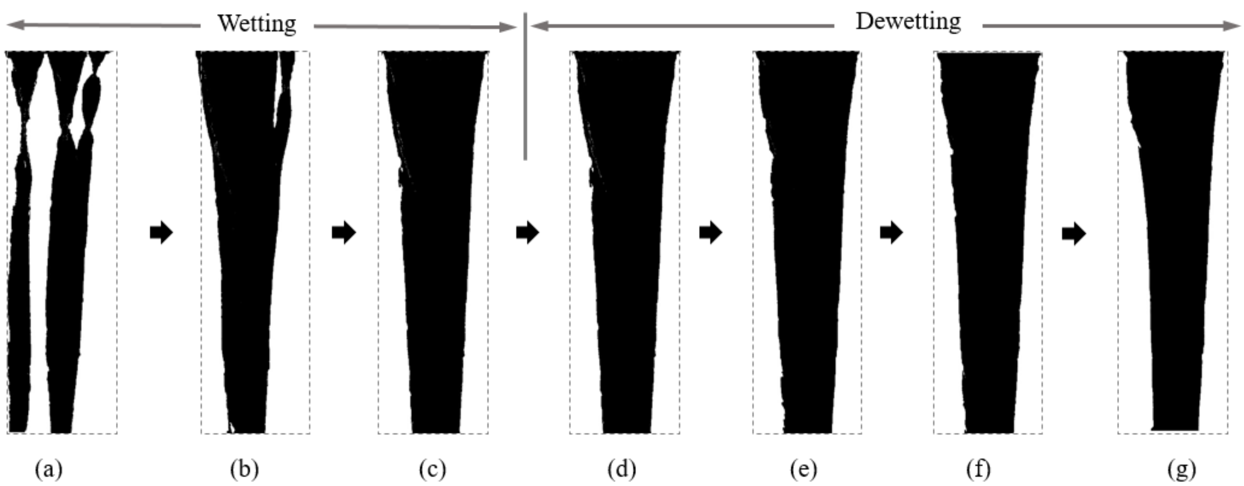

Figure 3: Binary images obtained for increasing and decreasing flowrate of 100mm in distributor width; (a) WR = 52.6%, Re_F = 1584, We = 0.32, (b) WR = 61.0%, Re_F = 2425, We = 0.16, (c) WR = 69.6%, Re_F = 3094, We = 0.10, (d) WR = 70.3%, Re_F = 2264, We = 0.18, (e) WR = 70.2%, Re_F = 1605, We = 0.31, (f) WR = 69.8%, Re_F = 741, We = 1.14, (g) WR = 66.3%, Re_F = 255, We = 6.81.

The binary images for the distributor width of 100mm are represented in Figure 3 by increasing and decreasing flowrate conditions. The results are noticed that a higher wetted area is obviously noticed when the flowrate is gradually increased in the wetting condition. On the other hand, in dewetting condition, the wetting ability can maintain with moderately decreased even the flowrate is considerably reduced. A higher wetted area is achievable when a given flowrate is obtained by gradually decreasing (Figure 3a) when it compares to a closely corresponding Film Reynold numbers of wetting condition (Figure 3e). Figure 4a – 4f represent examples of binary images for the case of 33mm distributor width.

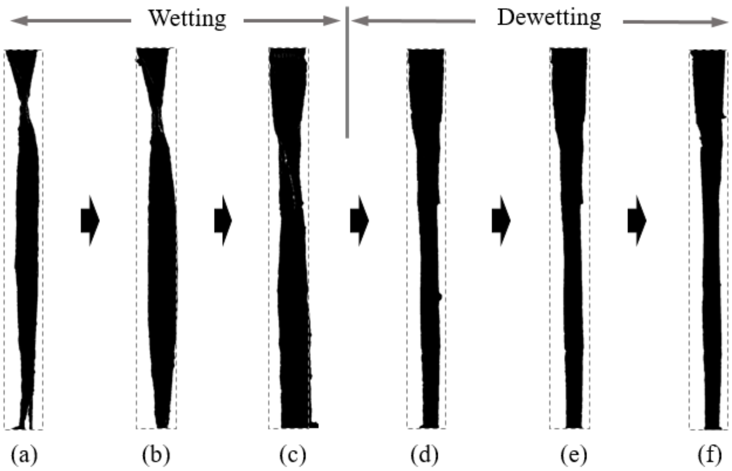

Figure 4: Binary images obtained for increasing and decreasing flowrate of 33mm in distributor width; (a) WR = 50.4%, Re_F = 1715, We = 0.27. (b) WR = 64.2%, Re_F = 2215, We = 0.18. (c) WR = 79.3%, Re_F = 4720, We = 0.05. (d) WR = 61.2%, Re_F = 2372, We = 0.16. (e) WR = 61.1%, Re_F = 1723, We = 0.28. (f) WR = 53.9%, Re_F = 642, We = 1.47.

The process is repeated for the full range of conditions (Figure 3 and 4), at increasing and decreasing flowrate conditions and for each distributor width (Figure 5). Since the maximum flowrate is limited by the maximum pump capacity and the volume of the buffer tank above the distributor, the maximum Film Reynolds number differs depending on the distributor width (Width = 200 mm: Re_F =1728, We = 0.29; Width = 100 mm: Re_F = 3094, We = 0.10; Width = 33 mm: Re_F = 4721, We = 0.05), leading to different maximum wetted areas. Additionally, from a qualitative observation of the flow in its transition from the film-like flow at the distributor to a rivulet-like flow, this phenomenon occupies a wider scale when a wider distributor is employed.

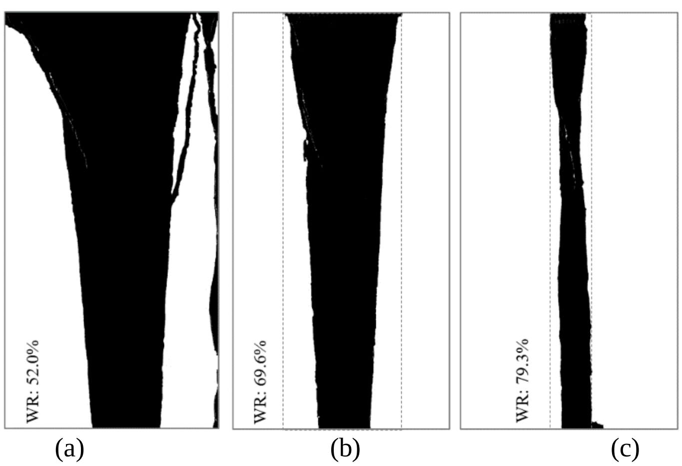

Figure 5: Binary images obtained maximum wetted areas for different distributor widths; (a) Width = 200 mm, Re_F =1728, We = 0.29. (b) Width = 100 mm, Re_F = 3094, We = 0.10. (c) Width = 33 mm, Re_F = 4721, We = 0.05.

The data obtained from the ratio of wetted to total area are plotted in Figures 6 and 7 as functions of Film Reynolds and Weber numbers, respectively. In general, it is observed that for increasing flow rates (increasing Film Reynolds and decreasing Weber numbers) the Wetted Area Ratio (WR) increases regularly following approximately the same trend independently on the distributor width.

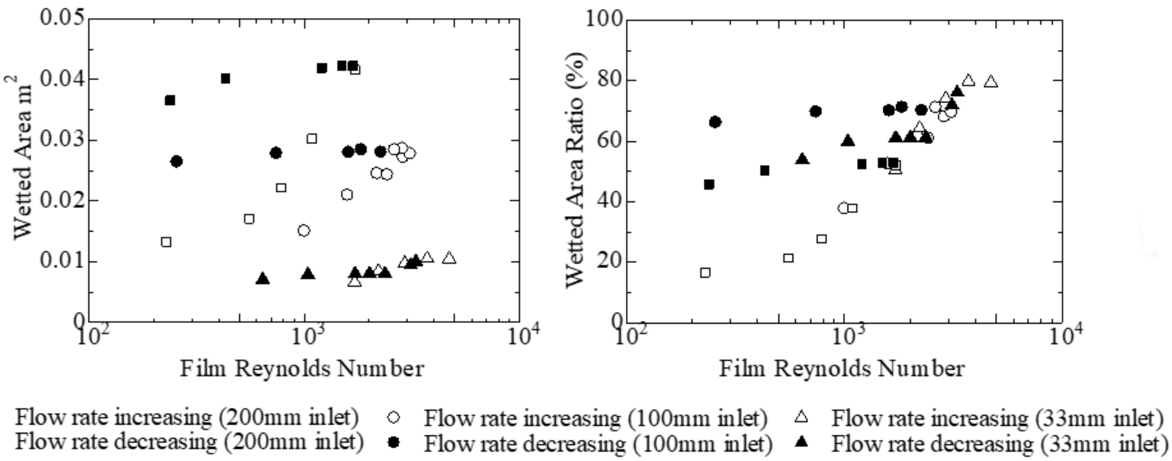

Figure 6: Wetted area and wetted area ratio (WR) against Film Reynolds number

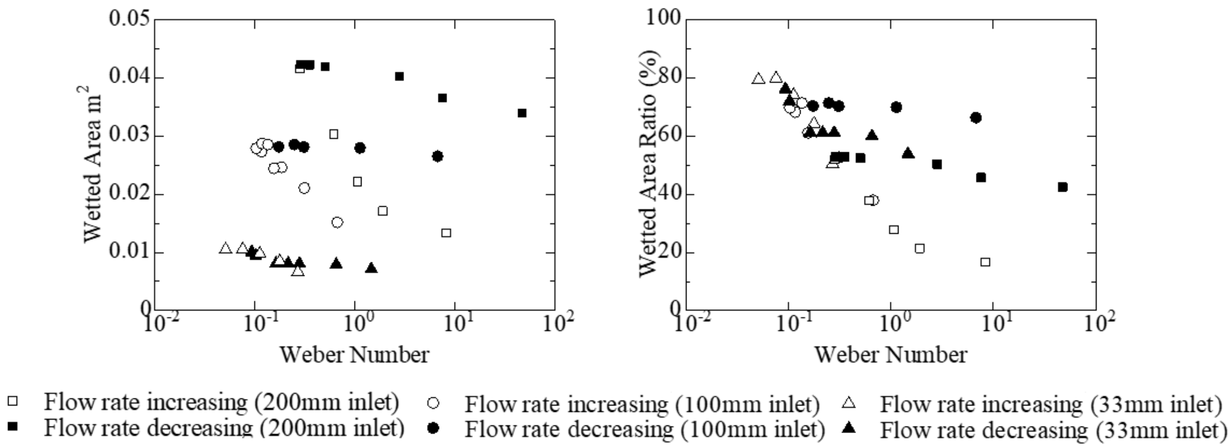

Figure 7: Wetted area and wetted area ratio (WR) against Weber number

As previously mentioned, different maximum wetted areas are achieved for different distributor widths, and, as the flow rate is decreased, the wetting ability of the flow follows a different trend, hence highlighting the occurrence of a hysteresis behavior. More specifically, a higher wetting ability is highlighted for decreasing flow rates, when compared to the increasing flow rate condition. This behavior can be related to the contact angle hysteresis occurring on a non-ideally smooth surface.

Regarding the influence of the distributor width, it can be observed that a higher distributor width (200mm) is associated to lower wetting ability and a steeper decreasing trend as the flow rate is decreased, when compared to a 100mm distributor. Accordingly, it can be stated that the 200mm distributor exhibits a lower wetting hysteresis than the 100mm one. However, the same observation cannot be applied to the results extracted with a 33mm distributor. It is likely that this geometry of the distributor has a dominant effect this small scale, and the rivulet flow appears more irregular in its shape, exhibiting an oscillating transversal width (Figures 4a-4b) and leading to a lower wetting ability than expected.

4. CONCLUSION

The wetting ability of pure water flow over a vertical flat aluminum surface has been investigated for three different distributor widths. Visual images of the experimental test section captured when increasing and decreasing the water flowrate have been analyzed by image processing to measure the wetted area and qualitatively describe the flow hydrodynamics. Finally, the influence of the distributor width on these quantities has been described.

A higher wetting ability has been highlighted for decreasing flowrates when compared to the increasing flowrate condition, thus delineating the hysteresis characteristics of the wetting behavior of this solid-liquid pair; a higher distributor width (200mm) has been associated to a lower wetting ability and a steeper decreasing trend as the flow rate is decreased, when compared to a 100mm distributor. Accordingly, the 200mm distributor exhibits a lower wetting hysteresis than the 100mm one. However, possibly owing to the excessively small scale of the distributor, the same observation could not be applied to the results extracted with a 33mm width. Additionally, from a qualitative observation of the flow in its transition from the film-like flow at the distributor to a rivulet-like flow, this phenomenon occupies a wider scale when a wider distributor is employed.

Further efforts are required for clarifying these phenomena on a wider range of flow rates including a fully wetted condition and different distributor widths.

NOMENCLATURE

A	Cross-section Area	(m^2)
b	Distributor's width	(m)
g	Gravity	($m \cdot s^{-2}$)
$\dot{m}$	Mass flowrate	($kg \cdot s^{-1}$)
Re	Reynolds number	(-)
u	Nusselt film velocity	($m \cdot s^{-1}$)
We	Weber number	(-)
WR	Wetted Area ratio	(-)

Greek symbols

Γ	Specific liquid load	($kg \cdot m^{-1} s^{-1}$)
δ	Film thickness	(m)
μ	Dynamic viscosity	($Pa \cdot s$)
ρ	Density	($kg \cdot m^{-3}$)
ν	Kinematic viscosity	($m^2 \cdot s^{-1}$)
σ	Surface tension	($J \cdot m^{-2}$)

Subscript

F	Film

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