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Experimental Study of Heat and Mass Transfer for Liquid Film Evaporation along a Vertical Plate Covered With a Porous Layer

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ABSTRACT

In this paper, we realized an Experimental study of heat and mass transfer for liquid evaporation along a vertical plate covered with a porous layer. To develop this study, an experimental dispositive was realized. To highlight the effect of the addition of a porous layer on the phenomenon of evaporation, we first study the case of the flow of a liquid film on an aluminium plate. Then we covered the same plate by a porous layer. We could measure the temperature along the plate and the evaporated flow using the test bed. From these measurements we note that temperatures are higher with the presence of the porous medium which affect positively on the evaporated flow. In addition, various dimensionless numbers were analyzed as the sensible and latent local Nusselt number, solving the energy equation by inverse method. We note that the latent Nusselt number is more important than the sensible Nusselt Number. Then the flow dissipated by evaporation is greater than that used by the film to increase its temperature. We also note that the calculated values of the latent and sensible Nusselt number are greater in the presence of the porous medium that proves that the addition of the porous layer improves heat and mass exchange.

Keywords: Heat and mass transfer; Evaporation; Porous layer.

NOMENCLATURE

A	amplitude of oscillation	Fy	component of the resultant pressure force acting on the lower side
a	cylinder diameter	f, g	generic functions
Cp	pressure coefficient	h	height
Cx	force coefficient in the x direction	i	time index during navigation
Cy	force coefficient in the y direction	j	space index
c	chord	α	angle of attack
dt	time step	γ	dummy variable
X	component of the resultant pressure force		

1. INTRODUCTION

The phenomena of heat and mass transfer are of considerable interest in the engineering field. This interest is reflected in many applications such as desalination, distillation, drying and cooling of electronic components.

Indeed, this topic has been the subject of several research studies for many years and brought together several lines of scientific work.

To improve the transfer, researchers have studied different geometries and conducted a parametric study on almost all input parameters that may influence transfers.

For instance, there are those who have studied the evaporation of a liquid film flowing on a flat plate (Siow, 2002).

Cherif, (2011) addresses the case of the evaporation of a liquid film on a vertical plate.

There are other researchers who are interested in the study of evaporation on an inclined plane, which

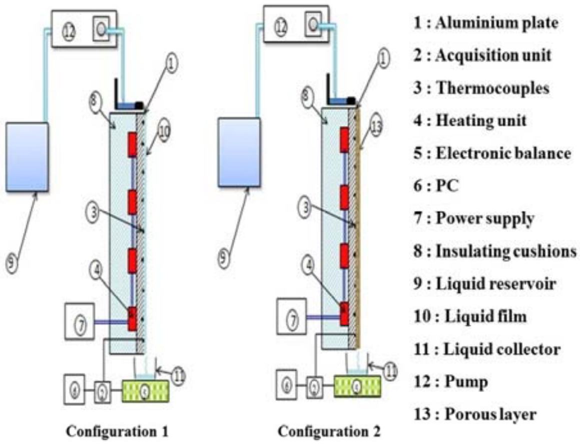


Fig. 1. The studied configurations.

affects gravitational forces and decreases the rate of fluid flow (Agunaoun, 1994).

In the other hand, the use of binary fluids was another solution to improve the heat and mass exchange (Debbissi, 2013).

However, obtaining a homogenous liquid film over the entire plate constitutes a major discrepancy between the theoretical and experimental studies. Despite efforts in the field of modeling and numerical simulation, we still see a difference between calculation and experiment. In a previous work of Cherif (2011), they have studied the two aspects of evaporation film: experiment and simulation. A difference was reported. They believe that this difference is caused by the difficulty of making a falling film on a vertical plate. In fact, the film can't be controlled if it is directly adhered to the plate.

To analyze the effect of dry zones on the plate, Mammou (1992) numerically studied the evaporation along an inclined plate. This plate consists of two wet zones separated by dry zone. The results of this study showed that the length of the dry zone plays an important role.

More recent studies have explored various techniques to solve this problem. For example, several researchers have used rough surfaces, interposed obstacles (Zheng 1999), used a porous layer that covers the plate or have used a corrugated plate (Gonda, 2014).

As a result, this work focuses on the study of the flow of a liquid film on a vertical plane covered by a porous layer. The main objective is to evaluate the effect of the presence of the porous layer on the phenomenon of evaporation.

2. EXPERIMENTAL FACILITY

The following section outlines general (non-formatting) guidelines to follow. These guidelines are applicable to all authors and include information on the policies and practices relevant to the publication of your manuscript.

2.1 Setup

To conduct the study, we realized an experimental setup, completed by a measurement system that allows the automatic acquisition of the temperatures measured by the different thermocouples installed along the plate.

The experimental setup is composed of a plate of aluminum in size 1000*500*12 mm. Electrical resistors connected to the generator are distributed homogeneously over the entire rear face of the plate which forms the heating system. To avoid losses of heat flow, a glass wool layer and a Plexiglas wall were placed around resistances. We set a reservoir of water above the plate, which, once full, it is drained by overflow, thus creating water film flowing homogeneously on the exchange surface.

After the realization of all tests for the evaporation of a liquid film on a vertical plate (configuration 1), we covered the exchange surface with a porous layer and thus, we passed to the second configuration.

Fig. 2. Schematic of the experimental setup.

2.2 Measurements

To study the effect of the presence of the porous medium on the evaporation phenomenon, we first conducted the experimental tests for the case of the flow of a liquid film on a vertical plate (configuration 1). Next, we spent the second configuration by covering the plate with a porous layer of the same size and thickness of 1 cm.

The heat flow and the water inlet flow appear as operating parameters whose influence should be studied. For this, tests are realized for different heating power from 400 W to 1400 W and for two water inlet flow (min = 2.77 g.m-2.s-1 and min = 4.44 g.m-2.s-1)

Table 1 contains the variation ranges of the experimental conditions.

3. Results and discussions

3.1 Temperature evolutions

Before starting the tests in the presence of the liquid film, it is interesting to study the effect of adding the porous layer in natural convection without phase change (without liquid). For this, we represent in fig 3 the temperature variation throughout the plate without and with porous medium.

Table 1 Variation range of the experimental conditions

Variables	Minimum	Maximum
Ambient temperature (°C)	16	25
Inlet water temperature (°C)	15	22
Water inlet flow ($g.m^{-2}.s^{-1}$)	2.77	4.44
Heat flow ($W.m^{-2}$)	800	2800
Humidity (%)	40	65

For reasons of safety and compliance with operating limits of heated components, we have chosen to study the case of natural convection only for a heat flow equal to 800 W.m-2. First, we note that the temperature increases from bottom to top of the plate, the area near the plate is hotter, the density decrease and therefore creating a flow of air near of the plate. Fresh air is sucked towards the plate which explains this temperature difference between the upper area and the lower area of the plate. Moreover, we note that the measured temperatures are much higher in the presence of the porous medium. We will see later, the effect of the increase of temperature on the evaporation phenomena.

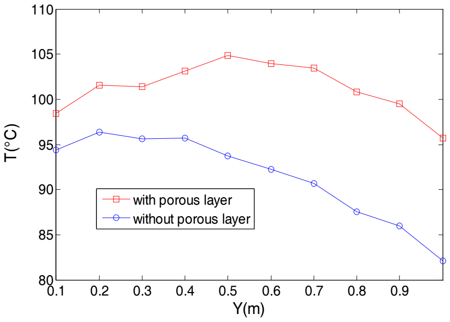


Fig. 3. Variation of the temperature throughout the plate in natural convection (q = 800 $W.m^{-2}$).

We represent in Fig. 4, the evolution of the temperature along the plate for different heat flow and different liquid inlet flow. As in the case of natural convection, the temperature measured in the presence of the porous layer are higher. Indeed, the fact of covering the plate by a porous layer creates a kind of thermal resistance at the exchange area, which will be beneficial for the evaporation process. Moreover, we note that the profiles of the temperature are divided into two areas: the first area begins from the top of the plate (entrance of liquid) to the point where the temperature reaches its maximum. In this area of the plate, the liquid heats up during its descent without significant evaporation, this explains the linear and remarkable increase of the temperature. From the point where the temperature reaches its maximum to the bottom of the plate, we note that the temperature is almost constant: the evaporation zone.

This result is proved in the work of Jabrallah (2005), who has demonstrated the existence of these two zones in the case of the evaporation of a film liquid flowing on the wall of a vertical cavity.

It is noted also that during the evaporation without the porous medium, the heating zone defined previously, is spread over a larger area. Thus the liquid is heated more quickly and the temperature becomes more stable in the presence of the porous medium.

Obviously, the temperature increase with increasing the heat flow. However, we find that in the presence of the porous layer, the temperature measured for a heat flow equal to 2400 W.m-2 and 2800 W.m-2 are almost identical. So it can be concluded that the addition of energy brought to the liquid is completely consumed by the phase change, which proves that the presence of the porous medium minimizes the loss of energy by convection.

3.2 Resolution of the heat equation by the inverse method

Certainly, knowing the temperature at any point of the wet wall requires special interest in understanding the phenomenon of evaporation. But the knowledge of the local variation of the evaporated flow is essential. For this, and from the values of the measured temperatures, we must solve the heat equation on the plate. This resolution allows us to determine the values of the exchange coefficient at the wet wall and determine subsequently the variation of evaporated flow. The heat equation can be expressed by:

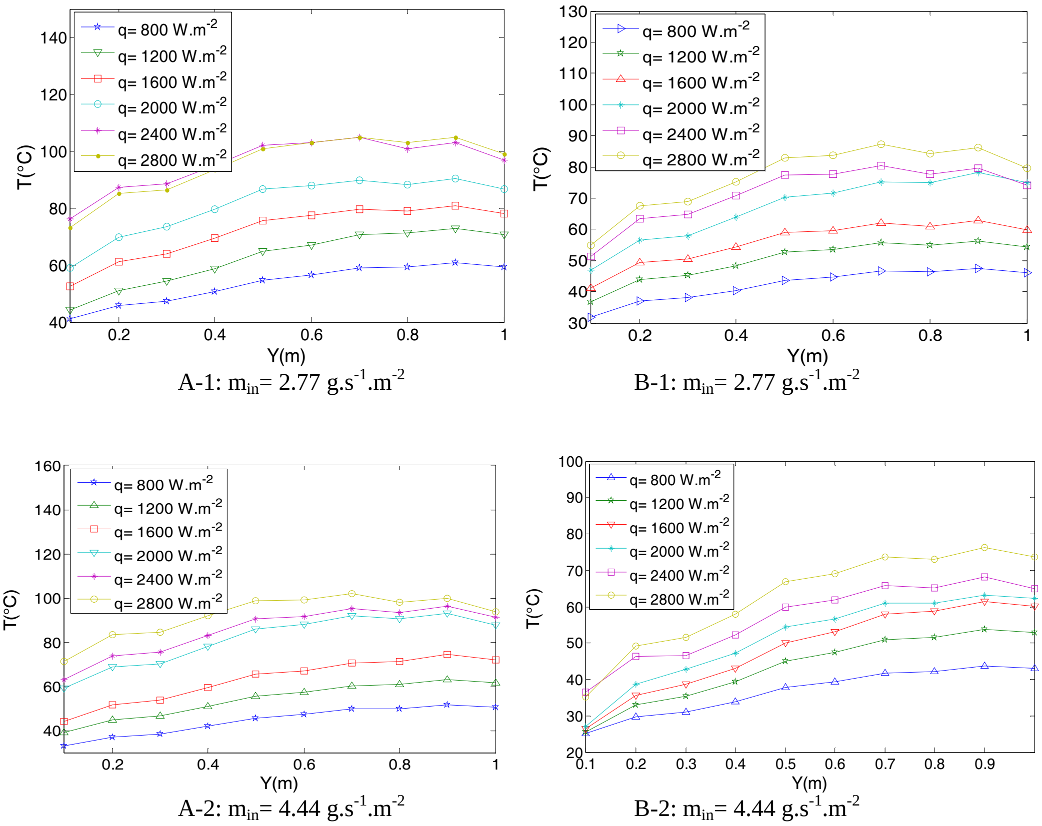


Fig. 4. Variation of the temperature throughout the plate for different heat flow and different liquid inlet flow (A: With porous layer and B: Without porous layer).

$$p(x,y)+\lambda(\beta\frac{\partial^2 T}{\partial x^2}+\gamma\frac{\partial^2 T}{\partial y^2})=\frac{1}{e}(\phi_{ar}+\phi_{av})+\alpha\rho C_p\frac{\partial T}{\partial t} \quad (1)$$

Where, p is the intern production (W.m-3), assumed to be homogeneous throughout the electrical resistance. , is the flux density dissipated by the back (insulator) and the desired flux density corresponding to convection and radiation on the upper side (air-cooled) of the resistor.

To simplify the problem, we will assume that the problem is stationary and in two dimensions, which means that:

$$\frac{\partial T}{\partial t}=0 \quad (2)$$

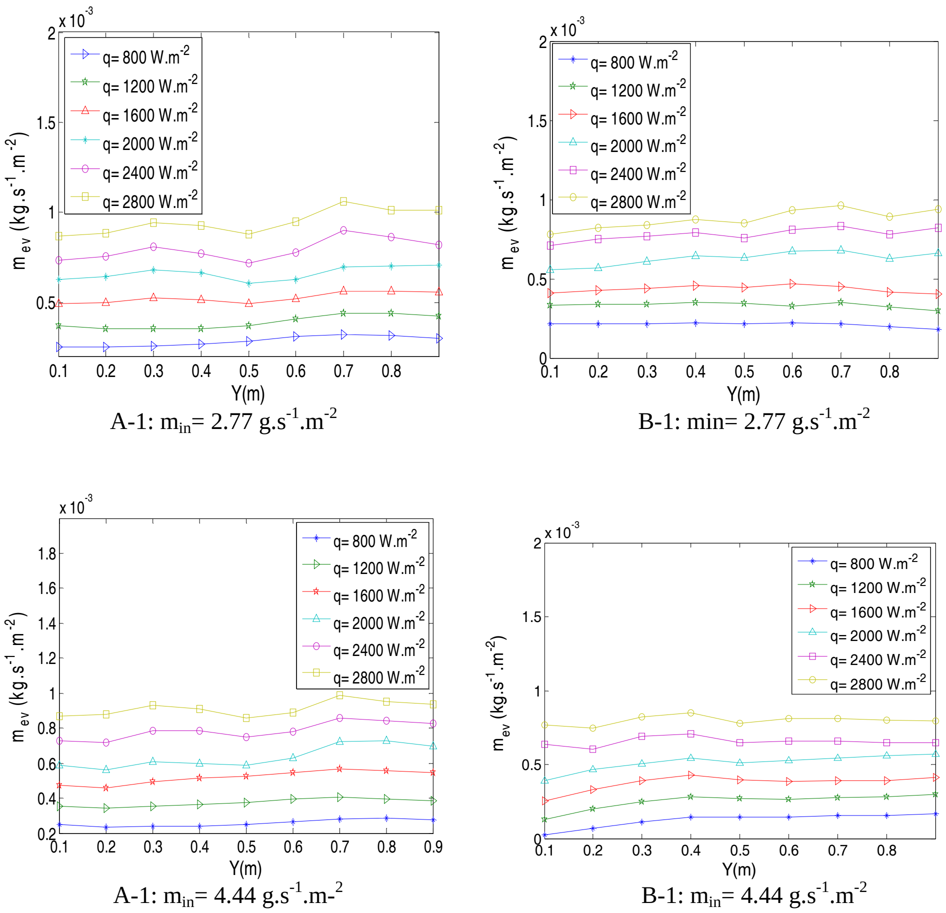
So the equation takes the following form:

$$p(x,y)+(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})=\frac{1}{e}(\phi_{av}) \quad (3)$$

The problem is a priori well-posed, since it has only one unknown, which is the conductive flux, and could therefore be the subject of a direct resolution. But the problem is the precision of the determination of the conductive flow in the resistance from the experimentally measured temperatures, which are noisy. It is more correct to implement an inverse resolution for this problem. More precisely the flow is determined by solving an inverse conduction problem, coupled to the direct thermal modeling of the general equation shown above, by finite differences. The principle is to impose the desired flow in the direct model and retrieve temperatures so deducted. The inverse method consists in the correction of the flow imposed from the comparison between the measured and numerical temperatures. So we must turn the difference between the temperatures calculated by direct method and measured temperatures to 0. Thus we aim to minimize the following criterion:

$$F=\sum_x\sum_y(T_{cal}(x,y)-T_{mes}(x,y))^2 \quad (4)$$

The minimization of this criterion alone does not regulate research and gives free rein to the amplification of errors in input data. Thus, we follow the method described by (Beck 1996 and Petit 2008). It consists of



A-1: m_{in}= 2.77 g.s^{-1}.m^{-2} B-1: min= 2.77 g.s^{-1}.m^{-2}

A-1: m_{in}= 4.44 g.s^{-1}.m-^{2} B-1: m_{in}= 4.44 g.s^{-1}.m^{-2}

Fig. 5. Local variation of the evaporated flow throughout the plate for different heat flows and different liquid inlet flow (A: With porous layer and B: Without porous layer).

adding the regularization terms to the previous criterion, and therefore we get:

$$F = \sum_x \sum_y (T_{cal}(x,y) - T_{mes}(x,y))^2 + \alpha_1 \sum_x \sum_y (grad(\phi_{av}(x,y)))^2 \quad (5)$$

3.3 Evaporated flow

Fig 5 shows the local variation of the evaporated flow along the plate for different heat flow and different liquid inlet flow.

The heat flow is the essential source of energy needed to the liquid-gas change phase. By observing the variation of the evaporated flow, we find that an increase in the heat flow leads to an improved evaporated flow. Indeed, an increase in the heating density expresses an energy addition which results in increases in thermal and mass gradients.

On the other hand, we see that increasing the liquid inlet flow, decrease the evaporated flow. This effect is explained by the fact that the contact time

between the film and the heated plate is shorter when the inlet flow is important. Indeed the film flows faster on the plate. So we can conclude that to upgrade evaporation, the system must operate at low water inlet flow.

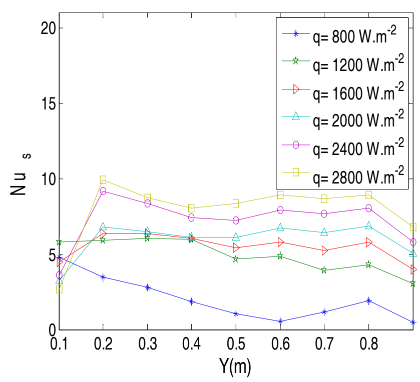
Moreover, we note that the evaporated quantities in the presence of the porous medium are more important. This is due to two major effects. The first, as mentioned previously, the temperatures measured in the presence of the porous layer are higher. The second effect is that the fact to cover the plate by a porous layer, improves the wettability. Indeed, the liquid infiltrates in the pores and thus covers the totality of the exchange surface.

4. Nusselt number

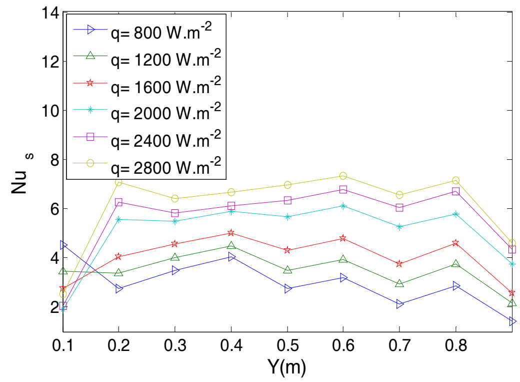
In order to generalize our study, heat and mass transfer along the plate were described by dimensionless numbers. The transfer of heat exchanged at the interface between the film of water and air is the sum of the convective flux and latent flux (Fedorov 1997).

$$\phi_T = \phi_S + \phi_L \quad (5)$$

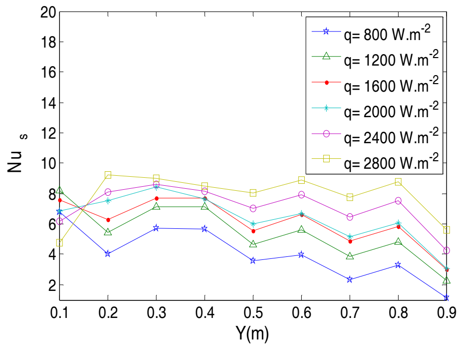
The local Nusselt number at the interface is defined as:



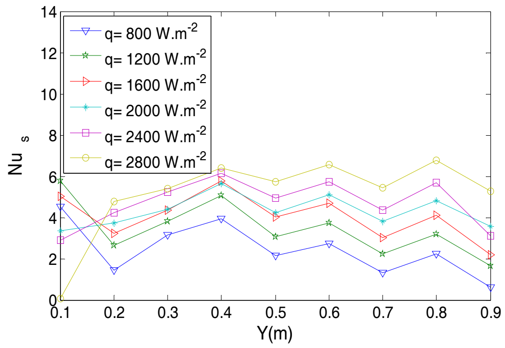
A-1: m_{in}= 2.77 $g.s^{-1}.m^{-2}$



B-1: m_{in}= 2.77 $g.s^{-1}.m^{-2}$

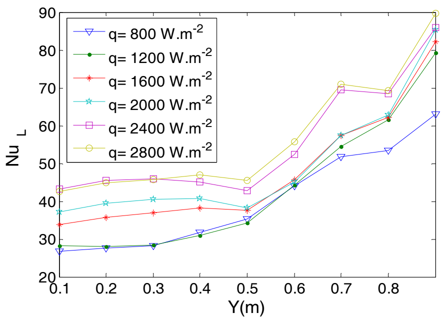


A-2: m_{in}= 4.44 $g.s^{-1}.m^{-2}$

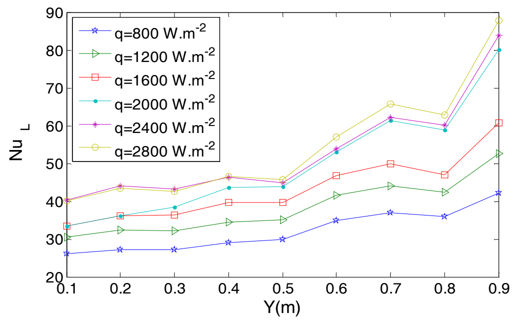


B-2: m_{in}= 4.44 $g.s^{-1}.m^{-2}$

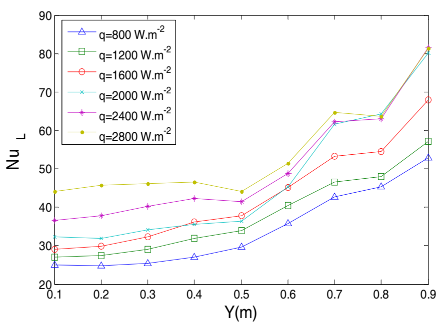
Fig. 6. Variation of the local sensible Nusselt number throughout the plate for different heat flows and different liquid inlet flow (A: With porous layer and B: Without porous layer)



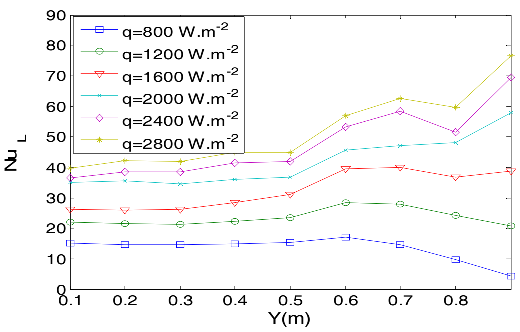
A-1: m_{in}= 2.77 $g.s^{-1}.m^{-2}$



B-1: m_{in}= 4.44 $g.s^{-1}.m^{-2}$



A-1: m_{in}= 4.44 $g.s^{-1}.m^{-2}$



B-1: m_{in}= 4.44 $g.s^{-1}.m^{-2}$

Fig. 7. Variation of the local latent Nusselt number throughout the plate for different heat flows and different liquid inlet flow (A: With porous layer and B: Without porous layer)

$$Nu = \frac{\phi_T}{\phi_{cd}} \quad (6)$$

May be consisted of two dimensionless numbers:

$$Nu = Nu_S + Nu_L \quad (7)$$

Where, Nus and NuL represent the sensible local Nusselt number and the latent local Nusselt number, describing respectively the sensible and latent transfer:

$$Nu_S = \frac{\varphi_S . L}{\lambda.(T_p - T_{L_{in}})} \quad (8)$$

$$Nu_L = \frac{\varphi_L . L}{\lambda.(T_p - T_{L_{in}})} \quad (9)$$

Fig. 6 represent the variation of the sensible local Nusselt number throughout the plate, for different heat flow and different liquid inlet flow.

As the evaporated flow, we note that the sensible Nusselt number increases with the increase of the heat flow and the decrease of the liquid inlet flow. We also note that the calculated values of the Nusselt number are significantly greater in the presence of the porous medium. Indeed, the use of a porous layer of copper improves the transfer from the heated plate to the liquid- gas interface, due to its high conductivity, which promotes the phase change and can evacuate more energy.

We represent in Fig 7 the variation of the latent local Nusselt number along the plate for different heat flux and different liquid inlet flows. First, we note that the latent Nusselt number increases with increasing heat flow and decreasing the liquid inlet flow.

We also note that the latent Nusselt number is more important than the sensible Nusselt number. The flow dissipated by evaporation is greater than that used by the film to increase its temperature.

In addition, the calculated values of the latent Nusselt number are greater in the presence of the porous medium that proves that the addition of the porous layer improves the mass exchange and therefore the evaporated flow.

5. CONCLUSIONS

This work focuses on the study of the flow of a liquid film on a vertical plane covered by a porous layer. The main objective is to evaluate the effect of the presence of the porous layer on the phenomenon of evaporation.

The most significant conclusions are as follows:

1-The liquid is heated more quickly and the temperature becomes more stable in the presence of the porous medium.

2-In the presence of the porous layer, the temperature measured for a heat flow equal to 2400 W.m-2 and 2800 W.m-2 are almost identical. So it can be concluded that the addition of energy brought to the liquid is completely consumed by the phase change, which proves that the presence of the porous medium minimizes the loss of energy by convection.

3-The evaporated quantities in the presence of the porous medium are more important. This is due to two major effects: The first is that the temperatures measured in the presence of the porous layer are higher. The second effect is that the fact to cover the plate by a porous layer, improves the wettability.

4-The Nusselt number are significantly greater in the presence of the porous medium. Indeed, the use of a porous layer of copper improves the transfer from the heated plate to the liquid- gas interface, due to its high conductivity, which promotes the phase change and can evacuate more energy.

5-the latent Nusselt number are greater in the presence of the porous medium that proves that the addition of the porous layer improves the mass exchange and therefore the evaporated flow.

6-The latent Nusselt number is more important than the sensible Nusselt number. The flow dissipated by evaporation is greater than that used by the film to increase its temperature.

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6. CONCLUSION

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ACKNOWLEDGEMENTS

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