THE INFLUENCE OF THE MENISCUS´ LIQUID BENDING IN THE CASE OF CAPILLARITY AT THE HEAT TRANSFER THROUGH MICRO FLAT HEAT PIPES

SPRINCEANA Siviu[1) 2)], **MIHAI Ioan**[1) 2)]

[1)] *Department of Mechanical Engineering, Stefan cel Mare University of Suceava, Romania, 13*
[2)] *Integrated Center for Research, Development and Innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for Fabrication and Control (MANSiD), Stefan cel Mare University, Suceava, Romania. e-mail: silviu_sprinceana@yahoo.com*

Abstract: *The knowledge of the functioning parameters of a micro flat heat pipe in the case of heat transfer, is important for the establishment of the heat flows which can be transported through the pipe. In the case of high heat flows, above 40W, the functioning of a micro flat thermal pipe (MTTP) could be disrupted through the limitations which appear due to thermodynamic biphasic processes which are developed at the limit. A better understanding of the heat transport mechanisms in the meniscus area of the liquid's filter, will directly help the designing of MTTP at a high efficient rate, also due to advanced systems of heat management. The evaporation process of the dispersed fluid in the interior of the capillary layer, takes place at the interface fluid - vapor's. The accumulation of vapors creates a unique prior pressure which allows, altogether with the capillary and adhesive forces, to ensure the filling with fluid the trapezoidal micro-channels which form the interior capillary layer of the MTTP. The pressure gradient which is necessary is intrinsic generated and contributes at the deformation of the meniscus´ liquid bending. In the analysis of forming the fluid film, there are considered hypotheses the one in which the fluid has a unidirectional flow on longitudinal direction, and the other one in which the pressure variation on transversal direction is neglected. This way, it can be considered that the pressure gradient of the fluid is the same on the whole utilized area.*

Keywords: *liquid meniscus, capillarity, convective heat transfer, heat flow.*

1. Introduction

To improve the performance of the heat transfer through MTTP, it is necessary to identify and understand better the thermodynamic phenomena which lead its' performances. Also, it must be taken into consideration that the optimization of the interior capillary structure can determine continuous heat transfer without a blockage of MTTP. Convective heat transfer phenomenon, which takes place during the heat transfer realized through MTTP, is produced after the application of a thermal flow on the vaporization area (figure 1) [Manimaran,2012]. In this case, the film thickness of the working fluid situated in the interior of the capillary structure is vaporized. Through fluid vapors movement resulted through the interior of MTTP, these transfer mass from the vaporization area to the condensation area. For equations, it is considered that MTTP is heated on the vaporization area through an electrical resistance while, on the on the condensation area is mounted a radiator with a fan to disperse the transported heat in the environment.

2. The considered input parameters.

To do the numerical calculations to dimension a MTTP according to the heat flow applied on an evaporator, it was considered that this would be made of a cooper pipe, closed at both ends, with an interior capillary structure made of trapezoidal micro-channels which use as working fluid distilled water [Sprinceană,2014].

For the following working fluid, there were considered the following thermo-physical parameters [3]: density $\rho_{lic}=996kg/m^3$, heat conductivity $\lambda_{lic}=0.632W/m\cdot K$, the coefficient of surface tension $\sigma_{lic}=0.0695N/m$, specific heat $c_{p.lic}=4019kg/KJ\cdot K$, the latent heat of vaporization for distilled water to $20°C$ is $h_{lg}=2454KJ/K$ and to $110°C$: $h_{lg}=2233KJ/K$, dynamic viscosity $\mu_{lic}=7.99\cdot 10^{-4}Pa\cdot s$. In numerical calculations, there were considered as gauge dimensions for MTTP (figure 1) the following figures: $L_{va}= L_{co}=35\cdot 10^{-3}m$, $L_{adb}=80\cdot 10^{-3}m$, $L_{ef}=150\cdot 10^{-3}m$, $H_{mttp}= 4\cdot 10^{-3}m$, $l_{mttp}=7\cdot 10^{-3}m$.

3. The heat transfer at the fluid-vapors interface.

On the vaporization area at an MTTP (figure 1) there is applied a heat flow which comes from a heat source, such as: a microprocessor or another electronic component.

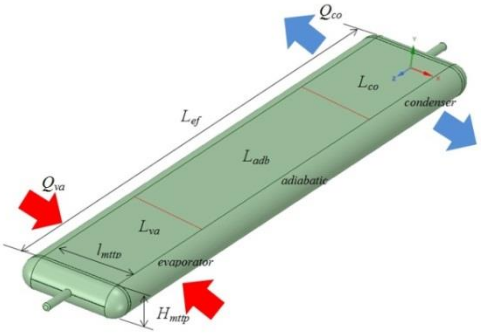

Figure 1: *The calculation areas at an MTTP*

In calculations it was considered $40W$ as being the maximum value of the heat flow. The working fluid (distilled water) diffused in the interior capillary structure goes through a biphasic transformation. The resulted vapors transport mass to the colder end of the MTTP (condenser). The vaporizations is associated with high coefficients of thermal transfer. This thing allowing the MTTP to transfer big heat tasks with low temperature differences between the evaporator and the condenser. To estimate if there appears a limitation of the heat transfer it is necessary to know the fluid from the trapezoidal micro-channels work, especially on the now formed meniscus, at the level of the vapors-fluid interface. From the data above, it is calculated the area from the vaporization and condensation area (S_{va}, S_{co}), perimeter MTTP (P_{mttp}) transversal aria of the MTTP (A_{mttp}).

$$S_{va}=S_{co}=2L_{va}\left(l_{mttp}+\frac{\pi H_{mttp}}{2}\right) \tag{1}$$

$$P_{mttp}=2l_{mttp}+\pi H_{mttp} \tag{2}$$

$$A_{mttp}=\frac{1}{4}H_{mttp}\left(\pi H_{mttp}+2l_{mttp}\right) \tag{3}$$

On the vaporization area, after it is applied a constant heat flow, it appears a transient thermal regime. The fluid vaporization from the evaporator is being applied the Clapeyron equation of boiling [Boughey,1999].

$$\Delta T_{crit}=T_{va}-T_{sat} \tag{4}$$

where: T_{va} – the wall temperature of the evaporator, T_{sat} – saturation temperature. The saturation temperature of the fluid-vapors mix from the interior of MTTP can be shown through the equation [Benafan,2008]:

$$T_{sat}=\frac{T_{va}L_{va}+T_{co}L_{co}}{L_{co}+L_{va}} \tag{5}$$

After the calculation of the saturation temperature, it can be calculated the heat transfer coefficient on the vaporization area:

$$h_{va}=\frac{4}{3}\sqrt[4]{\frac{\rho_{lic}{}^{2}\lambda_{lic}{}^{3}h_{lg}}{4\mu_{lic}\left(T_{va}-T_{sat}\right)L_{va}}} \tag{6}$$

The interior capillary structure at the MTTP is realized from trapezoidal micro channels longitudinally arranged on the interior walls. The working fluid is diffused in capillarity on the whole surface of the micro-channels. In figure 2 it was presented a portion from the internal capillary structure with the disposal of the working liquid in trapezoidal grooves.

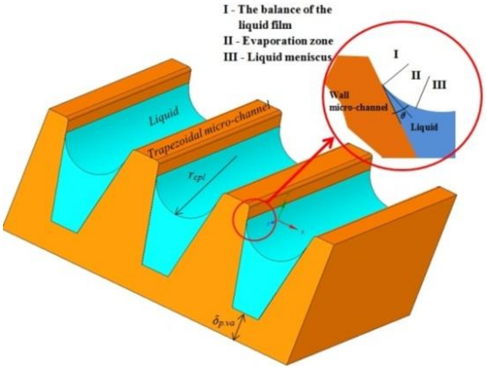

Figure 2: *Micro-channels trapezoidal section by working fluid.*

The heat transfer from the evaporator to the condenser is continuously realized if only the condensed fluid returns through capillarity at the evaporation area. The liquid vapors resulted after the evaporation process produce an interior heat increase which lead to an increase of the capillary pressure. The maximum value of the capillary pressure Δp_{cpl} for the remaining fluid in the trapezoidal micro-channels can be evaluated through La-Place equation [Boughey,1999][Benafan,2008][Vasiliev,2005].

$$\Delta p_{cpl} = \frac{2\sigma_{lic}}{r_{cpl}} \tag{7}$$

where r_{cpl} – capillary radius (figure 2, 3).

At the separation area between the vapors and the liquid surface from the trapezoidal micro channels, the interior pressure determines the apparition of a fluid meniscus which shows the areas provided in detail from the figure 2 [Mihai,2017]. It is considered that the evaporation takes place for a unidirectional fluid flow. The temperature at the vapors-fluid interface in the fluid's film region can be described by the equation of Clausius-Clapeyron [Anjun,2008]:

$$\left.\frac{dP}{dT}\right|_{sat} = \frac{h_{\lg}}{T_{sat}\left(\frac{1}{\rho_{vap}} - \frac{1}{\rho_{lic}}\right)} \tag{8}$$

In the first region of the fluid meniscus (figure 2), its density can be considered neglected. In this case, $1/\rho_{lic}=0$. Integrating the saturation temperature of the vapors T_{sat} and after the fluid's film temperature $T_{\delta,lic}$, the relation (8) becomes:

$$T_{vl} = T_{vap}\left(1 + \frac{\Delta P_{cpl}}{\rho_{vap} h_{\lg}}\right) \tag{9}$$

From (8) and (10) results:

$$T_{vl} = T_{vap}\left(1 + \frac{2\sigma_{lic}}{r_{cpl}\rho_{vap} h_{\lg}}\right) \tag{10}$$

Fluid's film bending from the wall of the micro-channel (region I - figure 3), in the absence of evaporation, it can be neglected. In this area, the temperature of the vapors-liquid interface T_{vl}, it will be considered equal with the temperature of the evaporator wall T_{va}. The major contribution of the second region at the fluid's film evaporation could be taken into account due to existence of dispersion and capillary forces. Nevertheless, there cannot be established a distinctive limit which separates the two regions.

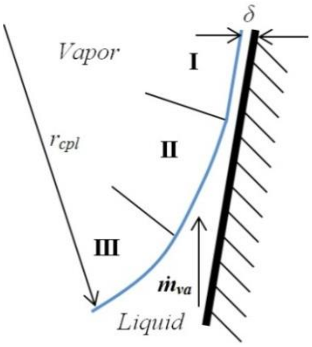

Figure 3: *Regions vapor-liquid interface.*

The mass flow of evaporated liquid in the second region can be calculated as in the equation [Anjun,2008] [Akkus,2015] [Bellur,2016] [Ranjan,2010]

$$\dot{m}_{va} = \frac{4}{3}\sqrt[4]{\frac{\rho_{lic}{}^{2}\lambda_{lic}{}^{3}h_{lg}}{4\mu_{lic}\left(T_{va}-T_{sat}\right)L_{va}}}\left(T_{vl}-T_{vap}\right)h_{\lg}{}^{-1}$$

(11)

To calculate the thickness of the liquid's film, it began with the constructive dimensions of the trapezoidal micro-channel, presented in figure 4. It was considered that the liquid from the micro-channels from the vaporization area is equally distributed. The capillary pressure produces the pumping of the liquid through the micro-channels, in the case when the capillary limit is not achieved. In this case, the angle formed by the liquid's film at the wall of the micro-channel is influenced by the capillary pressure and the pressure drop at the vapors - liquid $p_{c,vl}$ level interface. In this case, the equality (7) can be written as:

$$\Delta p_{cpl} = \frac{2\sigma_{lic}}{r_{cpl}} + p_{c,vl} \tag{12}$$

The pressure drop from the vapors-liquid $p_{c,vl}$ interface, it can be neglected when $h_l=0$.

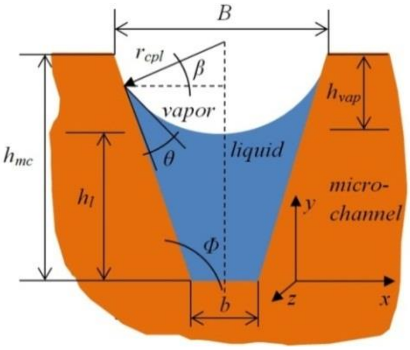

Figure 4: *Section through trapezoidal micro-channel.*

In the case of distilled water which was used as working liquid, $p_{c,vl}$ value can be expressed as:

$$p_{c,vl} = \rho_{lic} R T_{va} \ln\left(a\delta^b\right) \tag{13}$$

The a, b coefficients are in dependence with the thickness of the liquid's film, these being expressed according to the liquid's polarization and solid-liquid proprieties from the first region (figure 3). In case of distilled water (polar fluid) the value of the coefficients according to [Anjun,2008], could be approximated: $a=1.5787$, $b=0.0243$. Substituting (12), (13) in (9) it will be obtained the thickness of the liquid's film from the first region of the meniscus:

$$\delta = \exp\left[\frac{\left(\frac{T_{va}}{T_{vap}}-1\right)\left(\frac{h_{\lg}}{RT_{va}}\right)-\ln a}{b}\right] \tag{14}$$

To calculate the capillary radius there had been used the dimensions in figure 4. It was expressed the value of angle β, according to the angle of the liquid's meniscus at the wall of the micro-channel θ:

$$\beta = \theta - \left(\frac{\pi}{2} - \phi\right) \tag{15}$$

The value of the capillary radius will be influenced by the angle's value θ, which, in calculations, was expressed in circular measure:

$$r_{cpl} = \frac{\frac{B\sin 2\Phi}{2} + \left(h_{mc} - \delta_{p.va}\right)\cos 2\Phi}{\cos\beta \sin 2\Phi + \left(1-\sin\beta\right)\cos 2\Phi} \tag{16}$$

4. The obtained results and their interpretation.

The interior pressure drop on the vapors-liquid interface on the meniscus formed in the trapezoidal micro channels, affects considerably the thickness of the film in the first region, the temperature at the interface and the distribution of the thermal flow on MTTP. This action has consequences both over the capillary radius and over the heat transfer at the level of the trapezoidal channels.

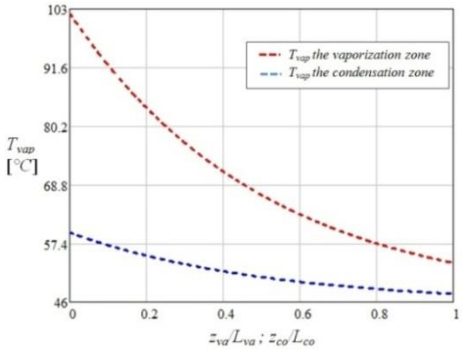

Figure 5: *Liquid-vapor temperature evolution depending on the dimensionless L_{va}, L_{co}..*

Using the relations above, it was created in Mathcad a source code which allows the calculation of the main parameters presented above. In figure 5 it was presented the variation of the vapors temperature in the moments of evaporation and condensation, according to the dimensionless ratio of the MTTP length. The dimensionless ration of the MTTP length represents the fraction between the instantaneous length z_{va} and z_{co} and the one of the total length of the vaporization area L_{va} and condensation one L_{co}. The two area were considered in the working hypothesis as being equals. The decreasing tendency of the temperature of the liquid's vapors in the vaporization and condensation areas, highlight the fact that, at thermal flows up to *40W*, the capacity of MTTP to transport the heat, is not affected [Mihai[1],2017] [Mihai[2],2017]. The capacity of pumping the accumulated condense in the condensation area through the capillary layer is possible, without any complications, thus it was not reached the capillary limit. The calculation of the heat transfer coefficient in the vaporization area, highlights the fact that this has a decreasing tendency, once the temperature increases (figure 6).To calculate the h_{va}, it was taken into consideration both the temperature of the vapors and the temperature of the MTTP's wall in the vaporization area.

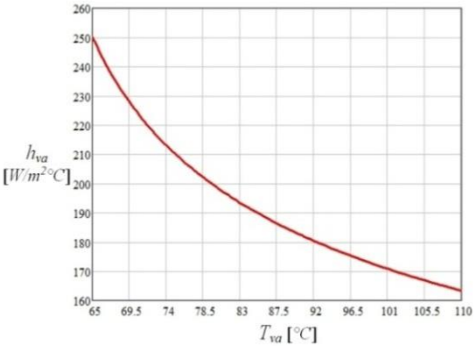

Figure 6: *Heat transfer coefficient of vaporization area depending on the wall evaporator temperature.*

The value of the heat transfer coefficient in the vaporization area, according to figure 6, decreases from $230 W/m^2 °C$ (for a temperature of $65°C$), to the value of $163 W/m^2 °C$ (for a temperature of $110°C$). The temperature from the evaporator wall was considered between $65 \div 110°C$. After the liquid vaporization from the evaporator, it appears an increase of the interior flow MTTP which at the vapors-liquid interface produces a modification in the meniscus radius. The modification of the meniscus radius produces a change in the contact angle's value θ, and, by default, a change in the thickness of the liquid's film. To calculate the capillary radius of the formed meniscus by the liquid from the trapezoidal micro channels with the walls of the MTTP's channels, it was taken into consideration that the angle θ has values between $0.25 \div 0.95$ [rad]. In figure 7 it was graphically represented the modification of the capillary radius of the meniscus according to the angle (θ) which is form by it with the wall of the micro-channel.

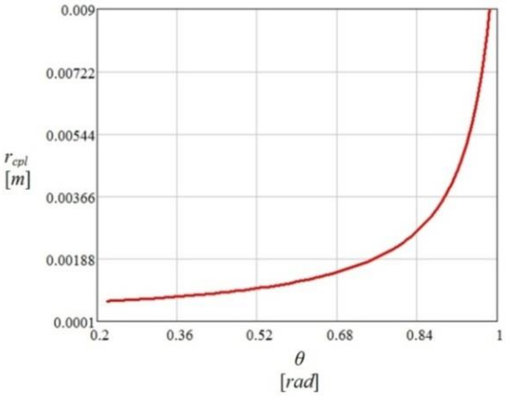

Figure 7: *Capillary radius variation depending on the θ angle.*

For the angle θ of the liquid meniscus, between $0.25 \div 0.95$ radians, the value of the capillary radius increases from $1.3 \cdot 10^{-4} m$ to $6 \cdot 10^{-3} m$. The mass debit of the evaporated liquid in the second region of the meniscus for vapours' temperatures between $80 \div 110°C$, is graphically represented in figure 8.

From the graphical representation presented in figure 8, it can be observed that the mass flow of the evaporated liquid on the second region of the meniscus, has a small variation in comparison with the modification of the angle θ, but only when the liquid vapors' temperature in the interior of the MTTP is constant.

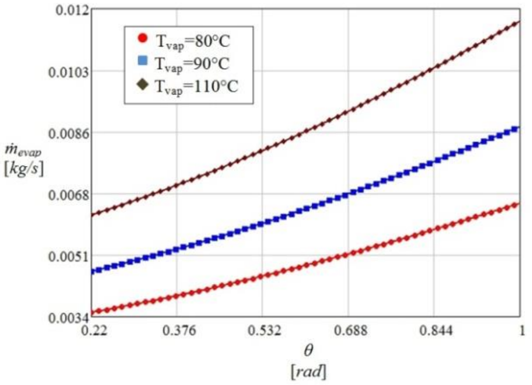

Figure 8: *Mass flow of evaporated liquid on region 2, depending on the θ angle.*

Furthermore, it was calculated the temperature difference at the vapors-liquid interface and the one of the vapors. The temperature values obtained for the vapors-liquid interface in comparison with the vapors' temperature are: the temperature for the interface vapors-liquid $T_{vl}=81.3°C$ and the vapors temperature is $T_{vap}=80.2°C$, respectively $T_{vl}=115.5°C$ and $T_{vap}=110°C$. The obtained results showed that the vapors-liquid interface's temperature is higher than the temperature of the liquid vapors, the temperature difference being between $1 \div 1.5°C$, the fact being highlighted in the graphical representation in figure 9.

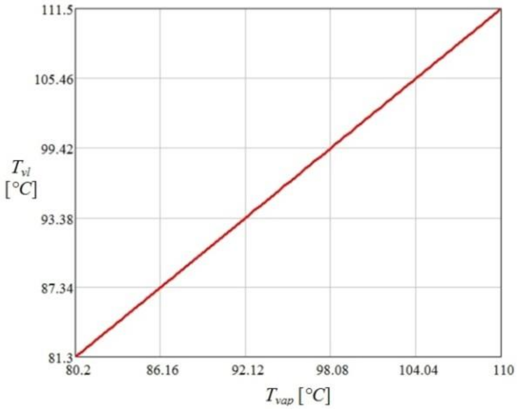

Figure 9: *Vapor-liquid temperature interface depending on the vapor temperature.*

Through the obtained temperature differences, it can be highlighted that, at the level of the liquid meniscus made from the trapezoidal micro-channels, it is produced an evaporation of liquid. By assumption, it is considered that the upper part of the liquid meniscus, respectively the first region, is at the temperature of vapors' saturation (*80°C*). In this case, an increase of temperature determines a play-out of the liquid's film, resulted from a higher heat transfer. It is compulsory to calculate the thickness of the liquid film δ from the first region to increase the vapors' temperature with *3°C*. In figure 10 there were graphically represented the results obtained for the modification of the thickness of the liquid film on the first region, according to the temperature of the liquid vapors from the interior of the MTTP.

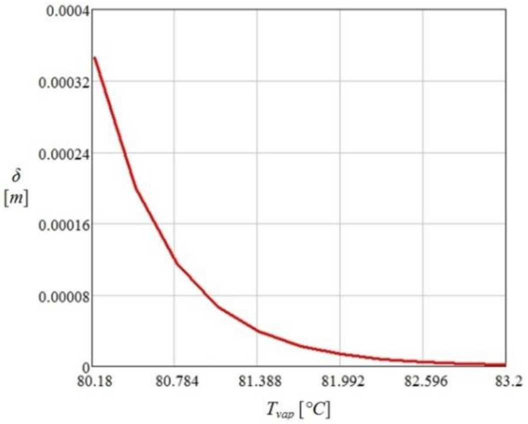

Figure 10: *Vapor-liquid temperature interface depending on the vapor temperature.*

It can be observed that around the vapors' temperature of *80°C*, the thickness of the liquid film, in the case when the working liquid is distilled water, it inclines to zero if the vapors' temperature increases with *3°C*. This thing happens when the angle's value *θ* inclines to *π/2*.

5. Conclusions

The contact angle of the liquid meniscus formed in the trapezoidal micro-channel of the interior capillary layer at MTTP, is very important in the determination of the capillary radius. The capillary radius is directly proportional with the contact angle, it determines the capillary capacity, the heat transport and the pumping capacity of the interior capillary layer. To maintain the heat transport capacity of the MTTP, it must be avoided the capillary limit. In this case, it is important to maintain the contact angle at values as low as possible. As a result, the evaporation area of the liquid meniscus amplifies, and ensures a heat transport capacity very efficient. With the help of the profile of the meniscus of the liquid film and the distribution of the heat flow in the evaporator, it can be verified how the MTTP reacts in the exploitation for different thermal fluxes.

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