THE BOILING OF THE REFRIGERANT R134a IN THE RECTANGULAR MICROCHANNELS OF THE CPU'S COOLING SYSTEMS

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Abstract: *The advanced technology must ensure a proper cooling of electronic components in order for those to operate at optimal temperatures. The heat transfer inside the CPU's cooling system is performed by heat exchangers, which include mini and microchannels. The cooling process with refrigeration agents represents an efficient solution.*

This article aims to study how the boiling process of the refrigerant R134a under goes in the rectangular microchannels of the cooling systems and, also, the manufacturing of such systems. Furthermore, it is presented a calculation model for heat transfer through rectangular microchannels at the boiling point. The calculation model used is validated by comparison with results obtained by other authors in specialized literature.

Keywords: *heat transfer, Refrigerant R134a, boiling, mini and microchannels.*

1. Introduction

The process of vaporization through mini and microchannels of some refrigeration agents in particular conditions of flow [1] was studied and considered by a high number of scientists.

Yan and *Lin* (1998) investigated the boiling process of the Freon R134a, which occured in horizontal minichannels with a hydraulic diameter D_h = 2 mm, a mass flow rate G = 50 – 900 kg/m^{2}s, a thermal flux q" = 5 – 20 kW/m^2, a Reynolds number Re = 506 - 2025.

Khodabandeh and *Palm* (2001) investigated the boiling process of the Freon R134a, localized in horizontal circular minichannels with the diameter of 1,5 mm, a mass flow rate G not measured, for a thermal flux q" = 28 – 424 kW/m^2.

2. Considerations regarding the cooling of CPUs by use of refrigeration agents

The cooling with refrigeration agents is part of the category of special cooling systems called "extreme", a method designed just for some users.

These cooling systems allow the temperature values of the CPU to be brought in the negative area. By using this method, the operation at maximum efficiency of the computer may be achieved, avoiding the overheating of the processor that may endanger its integrity.

The principle of operation (Fig. 1) of these cooling systems is the same with that of the refrigerator. In the system, compression is produced, condensing, expansion, and finally, the vaporization of the refrigeration agent. The processor is in direct contact with the vaporizer of the set-up where the refrigeration agent absorbs the heat produced by the processor when it evaporates, as it passes from liquid state to gaseous state.

The gas received from the vaporizer is compressed in the compressor and returns to liquid state in the condenser of the set-up, by condensation, that is, delivering heat to the environment. Thus, the pressurized liquid freon enters the thermal expansion valve, where, due to the Joule – Thomson effect, the temperature substantially decreases to its minimum value.

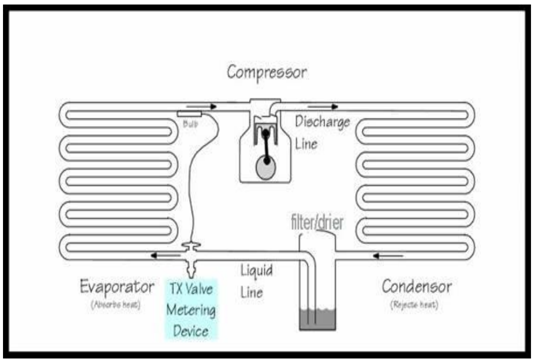


Figure 1: *The representation of the freon cooling process, [2].*

These cooling systems also include the systems "VapoChill" and "Prometeia".

Asetek, from Denmark, has been producing since 1997 the VapoChill series of CPU cooling units, Asetek Vapochill Micro Cooler in Fig. 2. The technology implemented in these units is called "Vapor Phase" cooling and it was proven to be ten times more efficient than water cooling and fifty times more efficient than air cooling, so that higher frequencies of processors were achieved.

Figure 2: *Cooler Asetek Vapochill Micro, [3].*

The Prometeia cooling system differs from the Vapochill system as it is not given as a kit, and consequently, it is harder to assembly.

The freon cooling systems offer a high degree of performance, these being able to cool the processor below 0 ºC. However, they also have a great disadvantage, that is, their high costs.

3. The calculation of heat transfer at boiling through rectangular microchannels

The calculation model proposed by [1] is applied to the boiling process of Freon R134a through microchannels that are directly engraved in the silicon chips. It is considered that the cooling is performed in order to dissipate the heat flux q"= 10 kW/m^2 from a processing unit of a computer.

Parallel microchannels have a rectangular section with a width a = 200 μm, a height b = 200 μm and a length L = 10 mm. The heated perimeter is P = b + a + b = 600 × 10^{-6} m, while the surface area is Ac = a × b = 40·10^{-9} m^2. By assumption, the contact angle θ_r is 20 degrees and Re = 100.

The refrigeration agent R134a has the temperature $T_{B,i}$ = 293,15 K at the entrance of the horizontal microchannels.

The properties of the Freon R134a, from [4, 5] at saturation temperature Tsat = 299,27 K and the pressure of 1 atm are: the dynamic viscosity of the liquid μ_l = 202 × 10^{-6} Ns/m^2, the dynamic viscosity of the vapours μ_v = 12 × 10^{-6} Ns/m^2, the density of the liquid ρ_L = 1206 kg/m^3, the density of the vapours ρ_V = 5,25 kg/m^3, the specific mass heat $c_{p,L}$ = 1199 J/kg K, the thermal conductivity of the liquid k_L = 82,4 × 10^{-3} W/mK, the thermal conductivity of the vapours k_V = 9,523 × 10^{-3} W/mK, the superficial tension of the liquid σ_L = 14,8 ×10^{-3} N/m, the latent heat of vaporization h_{LV} = 217,2 ×10^3 J/kg, the specific enthalpy of the liquid i_L = 591,47 x 10^3 J/kg, the specific enthalpy of the vapours i_V = 558,85 x 10^3 J/kg.

3.1. The location of the incipient phase of the boiling process

The location of the incipient phase of boiling and the radius of the cavity is determined by following the steps:

For some thermal flux, it is determined the temperature of the superheated wall:

$$\Delta T_{Sat,ONB} = \sqrt{8{,}8\sigma T_{Sat} q'' / \left(\rho_V h_{LV} k_L\right)} \qquad (1)$$

It is calculated the hydraulic diameter:

$$D_h = \frac{4A_c}{P_W} = a = b = 200 \times 10^{-6} m \qquad (2)$$

The Nusselt number for a rectangular microchannel with aspect ratio $\alpha_c = a/b = \mathbf{1}$ by Table 3.3 from [1], has the values $Nu_{fl,3}$ = 3,556 and $Nu_{fl,4}$ = 3,599.

The local heat transfer coefficient h is calculated as follows:

$$h = \frac{Nu k_L}{D_h}\left[W / m^2 K\right] \qquad (3)$$

The subcooling temperature will be:

$$\Delta T_{Sub,\mathrm{ONB}} = \frac{q''}{h} - \Delta T_{Sat,ONB}\left[K\right] \qquad (4)$$

The temperature T_B at the onset of nucleate boiling is:

$$T_{\mathrm{B,ONB}} = T_{Sat} - T_{Sub,ONB}\left[K\right] \qquad (5)$$

The flow speed V, by using the Reynolds number is:

$$V = \frac{\mathrm{Re}\,\mu_L}{\rho D_h}\left[m/s\right] \qquad (6)$$

The mass flow rate is:

$$\dot{m} = \rho V A_c \left[kg/s\right] \qquad (7)$$

The mass flux is:

$$G = \frac{\dot{m}}{A_c}\left[kg/m^2 s\right] \qquad (8)$$

We are interested in determining the onset of nucleate boiling (ONB). The incipient boiling location, by [1], is found at distance z from the entrance end:

$$z = \left(T_{\mathrm{B,ONB}} - T_{B,i}\right)\left(\frac{\dot{m} c_{p,L}}{q'' P}\right)\left[m\right] \qquad (9)$$

The radius $r_{c,crit}$ of the first cavity that will nucleate is found, by [1] as:

$$r_{c,crit} = \frac{k_L \sin\theta_r \Delta T_{Sat,ONB}}{2.2 q''}\left[m\right] \qquad (10)$$

3.2. The temperature variation of the superheated wall and subcooled liquid

The temperature variation of the superheated wall, represented in Fig. 3 in red, and the subcooled liquid, represented in Fig. 3 in blue, with respect the cavity radius of the cells for q” = 30 kW/m^2, is computed using relations from [1] as:

$$\Delta T_{Sat/\mathrm{ONB\_la\_}r_c} = \frac{1{,}1 r_c q''}{k_L \sin\theta_r} + \frac{2\sigma \sin\theta_r}{r_c} \frac{T_{Sat}}{\rho_V h_{LV}}\left[K\right] \qquad (11)$$

$$\Delta T_{Sub,\mathrm{ONB}} = \frac{q''}{h} - \Delta T_{Sat,ONB}\left[K\right] \qquad (12)$$

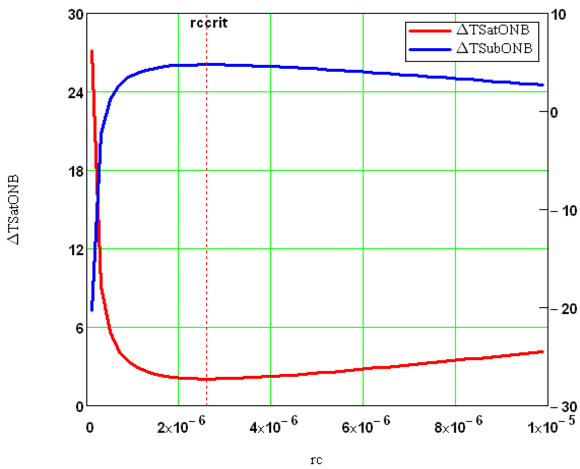


Figure 3: *A comparison between the variation* $\Delta T_{Sat/\mathrm{ONB}}$ - r_c *and the variation* $\Delta T_{Sub/\mathrm{ONB}}$ - r_c.

3.3. The pressure loss inside the section

The entrance length, for the developed laminar flow is calculated with the relation:

$$L_h = 0{,}05\,\mathrm{Re}\,D_h\left[mm\right] \qquad (13)$$

Because L = 10 mm > Lh, the assumption that the flux is completely developed is valid.

The place where the boiling starts to occur, coexisting in the two phases, is found at distance z_1:

$$z_1 = \left(T_{B,z} - T_{B,i}\right)\left(\frac{\dot{m}c_{p,L}}{q^{"}P}\right)[m] \quad (14)$$

The total pressure loss is calculated as a sum of the monophasic pressure loss until z and the biphasic pressure in the two phases from z to L.

$$\Delta p = \Delta p_c + \Delta p_{f,1-ph} + \Delta p_{f,tp} + \Delta p_a + \Delta p_g + \Delta p_e\,[Pa] \quad (15)$$

where:

- the components p_c, p_g, p_e can be neglected because the pressure loss is calculated in horizontal microchannels:
- the component $\Delta p_{f,1-ph}$ is calculated as:

$$\Delta p_{f,1-ph} = \frac{2(f\,\mathrm{Re})\mu_L U_m z}{D_h^2} + K(\infty)\cdot\frac{\rho_L U_m^2}{2} \quad (16)$$

where:

- the average speed Um = V;
- K(∞) is the Hagebnach factor calculated for rectangular channels with the relation:

$$K(\infty) = 0,6796 + 1,2197\alpha_c + 3,3089\alpha_c^2 - 9,5921\alpha_c^3 + 8,9089\alpha_c^4 - 2,9959\alpha_c^5 \quad (17)$$

The Poiseuille number (Po = fRe) for a rectangular channel is given by [1] as:

$$f\,\mathrm{Re} = 24(1 - 1,3553\alpha_c + 1,9467\alpha_c^2 - 1,7012\alpha_c^3 + 0,9564\alpha_c^4 - 0,2537\alpha_c^5) \quad (18)$$

This yields:

$$\Delta p_{f,1-ph} = \frac{2\cdot f\,\mathrm{Re}\cdot\mu L\cdot V\cdot z}{D_h^2} + K(\infty)\cdot\frac{\rho_L\cdot V^2}{2}[Pa] \quad (19)$$

The heated surface area in the region of the two phases is:

$$A_{h,tp} = (b + a + b)(L - z)\left[m^2\right] \quad (20)$$

The mass enthalpy (specific):

$$i_{TP} = i_{IN} + \frac{q^{"}A_{h,tp}}{GA_c}[J/kg] \quad (21)$$

The thermodynamic quality x_e:

$$x_e = \frac{i_{TP} - i_L}{h_{LV}} \quad (22)$$

In the calculations there is used the average quality x = x_{med} situated between 0 and x_e, x_{med} = 0,0047.

The Reynolds number for the vaporous part:

$$\mathrm{Re}_V = \frac{GxD_h}{\mu_V} \quad (23)$$

The vapour friction factor is:

$$f_V = \frac{f\,\mathrm{Re}_V}{\mathrm{Re}_V} \quad (24)$$

The pressure loss for the vaporous part:

$$-\left(\frac{dp_F}{dz}\right)_V = \frac{2 f_V G^2 x^2}{D_h \rho_V}[Pa/m] \quad (25)$$

The Reynolds number for the liquid part is:

$$\mathrm{Re}_L = \frac{G(1-x)D_h}{\mu_L} \quad (26)$$

The liquid friction factor is:

$$f_L = \frac{f\,\mathrm{Re}_L}{\mathrm{Re}_L} \quad (27)$$

$$-\left(\frac{dp_F}{dz}\right)_L = \frac{2 f_L G^2 (1-x)^2}{D_h \rho_L}[Pa/m] \quad (28)$$

The Martinelli parameter will be:

$$X^2 = \left(\frac{dp_F}{dz}\right)_L / \left(\frac{dp_F}{dz}\right)_V \quad (29)$$

Assuming both phases are laminar, a situation where is recommended, in [1] cap. 5, the value of constant C = 5, for which the amplification factor ϕ_L becomes:

$$\Phi_L^2 = 1 + \frac{C\left(1 - e^{-319 D_h}\right)}{X} + \frac{1}{X^2} \tag{30}$$

The component $p_{f,tp}$ is calculated as:

$$\Delta p_{f,tp} = \left(\frac{dp_F}{dz}\right) = \left(\frac{dp_F}{dz}\right)_L \phi_L^2 \left[Pa/m\right] \tag{31}$$

The pressure loss is:

$$\Delta p_a = G^2 v_{LV} x_e \left[Pa\right] \tag{32}$$

The total pressure loss will be:

$$\Delta p = \Delta p_{f,1-ph} + \Delta p_{f,tp} \left[Pa\right] \tag{33}$$

3.4. The thermal transfer coefficient on both phases

The convection number Co used in correlating the data of heat transfer when boiling is:

$$Co = \left[\left(1-x\right)/x\right]^{0,8} \left[\rho_V/\rho_L\right]^{0,5} \tag{34}$$

For numbers $Re_{LO} \leq 100$, the heat transfer coefficient for the liquid phase is calculated as:

$$h_{LO} = \frac{Nuk_L}{D_h}\left[W/m^2K\right] \tag{35}$$

The relation proposed in [1] for the heat transfer coefficient on both phases is:

$$h_{TP} = h_{TP,NBD} = h_{LO}\left\{0,6683 Co^{-0,2}\left(1-x\right)^{0,8} + 1058 Bo^{0,7} F_{Fl}\right\} \tag{36}$$

From the graphical representation, Fig. 4 can be observed the tendency to decrease of the heat transfer coefficient h_{TP} and the convection number Cox depending on the vapour quality, due to the laminar conditions and the dominance of nucleate boiling effects.

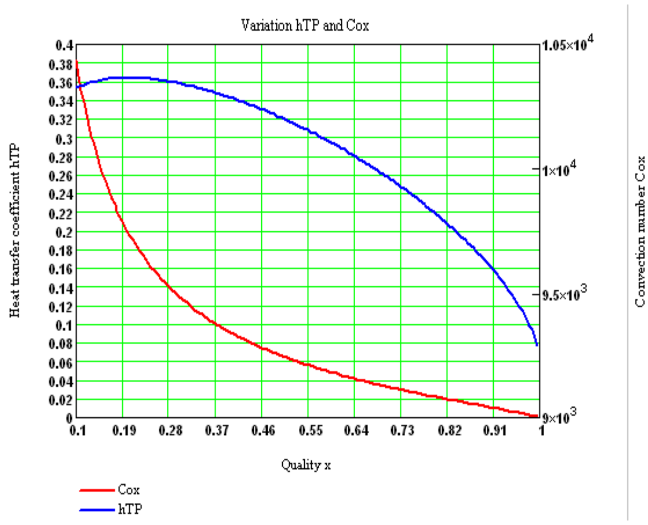
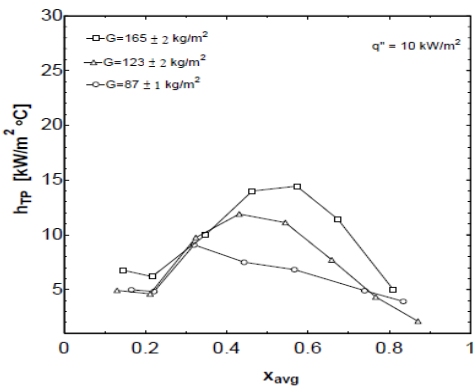


Figure 4: *The variation of the heat transfer coefficient and the convection number of title x, for Freon R134a.*

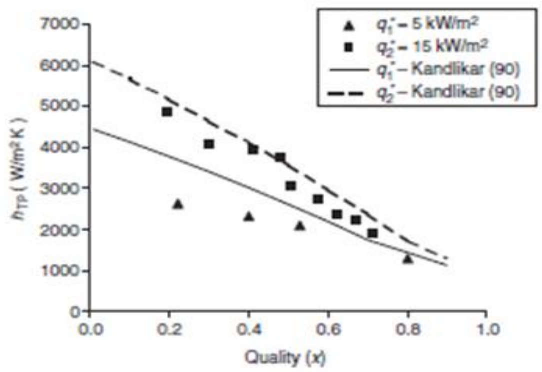
4. Validating the results

The liquid flow rate and the heat transfer in microchannels has great importance in a diversity of areas of interest, including in miniature thermal systems, in compact heat exchangers or in those designed for cooling electronics components.

X. Tu and P. S. Hrnjak, [6], carried out experiments in order to determine the flow rate and pressure drop in rectangular microchannels with D_h = 69,5 – 304,7 µm. They studied the heat transfer at the vaporization of the refrigerant R134a and also performed experiments with a thermal flow rate of 10, 15 and 20 kW/m^2, as well as with a mass flow rate of 87, 123 and 165 kg/m^2·s. They analysed the effect of the vapour title x on the heat transfer coefficient h_{TP} (Fig. 5.a), while a similar study (Fig 5.b) was performed in 1998 by Yan and Lin, cited in [1].



a.



b.

Figure 5: *The variation of the heat transfer coefficient h_{TP} with respect to the title of the x vapours:*
a – The variation of h_{TP} obtained by Tu and Hrnjak, [6];
b – The variation of h_{TP} obtained by Yan and Lin, [7].

By comparing the calculated values for the Freon R134a from Fig. 4, with those determined by other authors, Fig. 5, it can be observed the same way of variation and the same variation graphic.

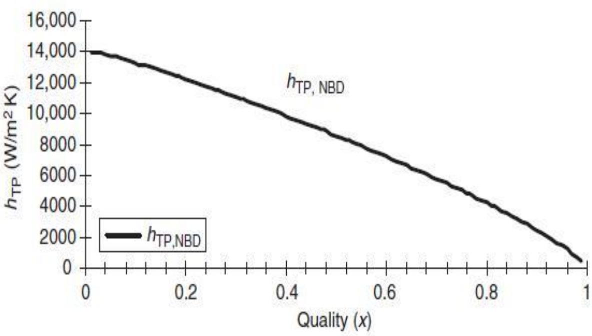


Figure 6: *The variation of the heat transfer coefficient on both phases with respect to x, for Freon R123, [1].*

There have been carried out calculations for determining the heat transfer coefficient for other types of freons, like R123. In Fig. 6, [1], can be observed, even in this case, a similar tendency of evolution of the heat transfer coefficient with respect to the vapours title.

Consequently, on the basis of the comparison between the results obtained by calculation with those obtained by other authors, the calculation model is valid.

5. Conclusions

The cooling systems with phase change represent a high-quality solution for the future. It is shown that "theoretically, there can be reached cooling capacities of 700 W/cm², in the situation when all the refrigeration agent vaporizes", [8].

The acquired results, represented in Fig. 4, show the same variation tendency and also the same variation curve of the heat transfer coefficient as those obtained by other authors in Fig. 5, 6 [1, 7, 8]. Thus, the obtained results are validated.

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