EVAPORATION OF THE HETEROGENOUS LIQUID FLOW FORCED BY THE MAGNETIC FIELD OVER A WALL

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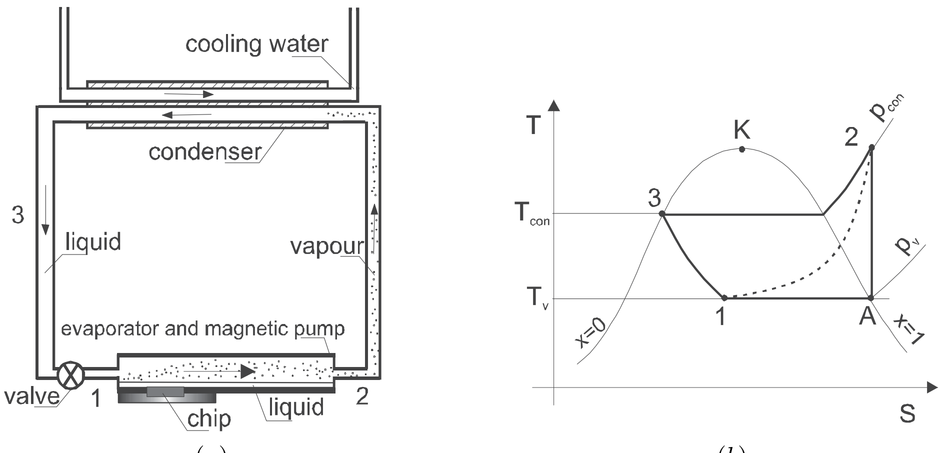
Introduction. One of the most important problems in modern technology is the cooling of electronic devices and the limitations set on the maximum temperature [1], which cannot exceed the acceptable value to secure correct work of a device. The solution to the cooling problem is of crucial importance for the proper work of these elements, which get heated in time with great intensity. The effective cooling of these elements is also very important.

Recently, an investigation has been carried out to develop an MEMS (Micro-Electro-Mechanical Systems) based micro cooling device [2]. This new method is a very efficient technique to remove heat from chips by surface evaporation of the chilling liquid. This problem is very relevant thus there is an urgent need to develop efficient cooling technologies.

It is of crucial importance to make use of devices, which can create electric and magnetic fields. The fields are designed for realization of the cooling process. Theoretical magnetic fluid flows in pipes have been investigated [3, 4, 5]. The velocity profile in the channel and the resistance of magnetic laminar flows were defined.

We are aiming at obtaining a higher level of cooling. We show a refrigeration cycle which is a slightly modified Linde cycle. The present study focuses on the prediction of the distribution of temperatures of both the cooling liquid layer and the cooled element.

1. Presentation of the cooling device. The magnetic fluid flows inside the refrigeration device. In Fig. 1 we can see both the schematic diagram and the theoretical cycle of the chip being cooled. The work and the heat are generated by a magnetic pump and the chip, respectively. As a result, the pressure and thereby



(*a*) (*b*)

Fig. 1. (*a*) Schematic diagram of a refrigeration vapour process. (*b*) Refrigeration cycle.

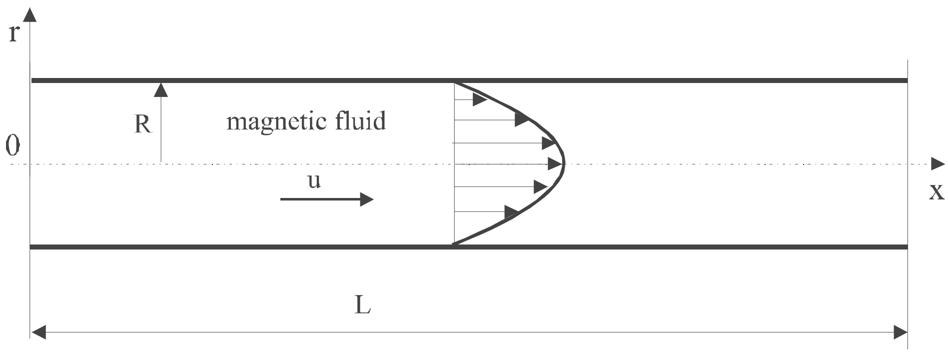


Fig. 2. Flows of magnetic fluid in the pipe.

the temperature are increased, as shown in lines 1-2. This process is composed of two phases: a vapour process 1-A, in which the chip supplies heat, and an isentropic compression process in the ideal cycle A-2.

The working medium then enters a condenser in which heat is extracted, resulting in a saturated liquid. By using an expansion valve the pressure irreversibly decreases. A throttling process is employed in which enthalpy remains constant 3-1.

This expansion process is a non-equilibrium process, so the area under the T-s diagram does not represent the net work input.

2. Pressure and driven flows of a magnetic fluid in a pipe. The laminar flow of a magnetic fluid, which has the density ρ and the kinematic viscosity ν with paramagnetic particles in a cylindrical tube of radius R and length L in the presence of a non-uniform axial magnetic fluid is studied. The flow of the fluid is driven by a constant pressure gradient $-\mathrm{d}p/-\mathrm{d}x > 0$. The model of the phenomena is presented in Fig. 3.

The basic linear momentum equation for an incompressible magnetic fluid (fluid composed of super-paramagnetic particles) in the dimensionless variables for a unidirectional axisymmetric flow in a tube has the form, as obtained by Cunha and Sobral [3]:

$$\frac{\mathrm{d}^2 u}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}u}{\mathrm{d}r} - \varepsilon\left[\left(\frac{\mathrm{d}u}{\mathrm{d}r}\right)^2 + 1\right] = \mathrm{Re}\cdot\Pi\,, \tag{1}$$

where:

- the dimensionless velocity u, which is equal to the ratio of the real velocity w and the average velocity $\overline{w}$ of the flow,
- the dimensional radius $r = r_1/R$,
- the dimensional axis $x = x_1/R$,
- the Reynolds number $\mathrm{Re} = \bar{w}\cdot R/\nu$ (ν – viscosity of the fluid),
- the small parameter ε depends on the magnetization relaxation time, the Reynolds number Re, the magnetization of the fluid and the magnetic field, which is dependent on the location of the x-axis,
- the dimensionless parameter of pressure p

$$\Pi = \frac{1}{\rho\cdot\bar{w}^2}\frac{\partial p}{\partial x}.$$

The equation was solved by the regular perturbation method for the velocity profile as a function of the magnetic and flow parameters [3]. The fluid velocity on the wall of the pipe vanishes.

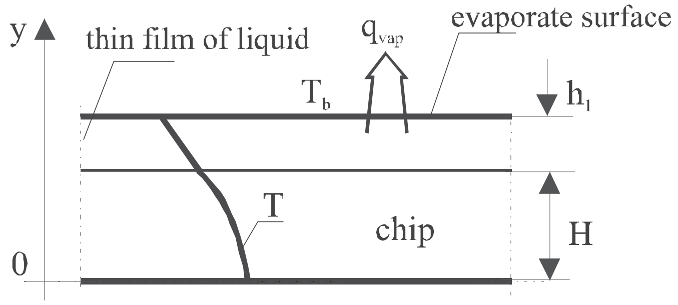


Fig. 3. Scheme of chip cooling.

The above mentioned solution of equation (1) makes it possible to obtain the volume flow of the fluid by the following equation

$$\dot{V} = \iint_S u \cdot \mathrm{d}S = \int_0^{2\pi} \int_0^R u\,(r) \cdot r \cdot \mathrm{d}r = 2 \cdot \pi \int_0^R u\,(r) \cdot r \cdot \mathrm{d}r, \tag{2}$$

which indirectly renders it possible to determine the rate of refrigeration of the chip. It will be the subject of further consideration.

3. Cooling of the chip. The differential equations of heat conduction in the chip and in the thin layer of liquid (see Fig. 4) have the dimensionless forms:

$$\frac{\partial^2 \theta_\mathrm{c}}{\partial y^2} + B_C = \frac{\partial \theta_\mathrm{c}}{\partial \tau}\,, \qquad \frac{\partial^2 \theta_\mathrm{l}}{\partial y^2} = \frac{\partial \theta_\mathrm{l}}{\partial \tau}\,, \tag{3}$$

which make it possible to find the temperature distributions. We assume that the following set of dimensionless parameters was introduced in the above equations: time, co-ordinate, liquid layer, chip temperature and liquid temperature

$$\tau = \frac{a_\mathrm{c} \cdot t}{H^2}\,, \quad y = \frac{y_1}{H} \quad h = \frac{h_1}{H}\,, \quad \theta_\mathrm{c} = \frac{T_\mathrm{c} - T_0}{t_\mathrm{b} - T_0}\,, \quad \theta_\mathrm{l} = \frac{T_\mathrm{l} - T_0}{t_\mathrm{b} - T_0}$$

where the parameter $B_C = \dfrac{\dot{q}_v \cdot H^2}{T_\mathrm{b} - T_0} \cdot \dfrac{1}{\lambda_\mathrm{c}}$ is the volume of the source of heat, and another dimensionless parameter

$$q_\mathrm{vap} = \frac{H}{\lambda_\mathrm{c}\,(T_\mathrm{b} - T_0)}\dot{q}\,,$$

denotes the stream heat from the surface of the liquid, where: $\dot{q}$ is the vapour heat, $\dot{q}_v$ is the source of heat, T_b is the boiling temperature, T_0 is the initial temperature, λ_c is the thermal conductivity of the chip, λ_l is the thermal conductivity of the liquid $\left(\tilde{\lambda} = \lambda_\mathrm{l}/\lambda_\mathrm{c}\right)$, a_c is the thermal diffusivity of the chip.

The total expression for both the boundary and the initial conditions may be written as:

$$\begin{gathered} \frac{\partial \theta_\mathrm{c}}{\partial y} = \tilde{\lambda}\,\frac{\partial \theta_\mathrm{l}}{\partial y} \quad \text{and} \quad \theta_\mathrm{c} = \theta_\mathrm{l} \quad \text{for} \quad y = 1\,, \\ -\frac{\partial \theta_\mathrm{l}}{\partial y} = q_\mathrm{vap} \quad \text{and} \quad \theta_\mathrm{c} = \theta_\mathrm{l} \quad \text{for} \quad y = 1 + h\,, \\ \theta_\mathrm{c} = \theta_{\mathrm{c}0} \quad \text{and} \quad \theta_\mathrm{c} = \theta_{\mathrm{l}0} \quad \text{for} \quad \tau = 0\,. \end{gathered} \tag{4}$$

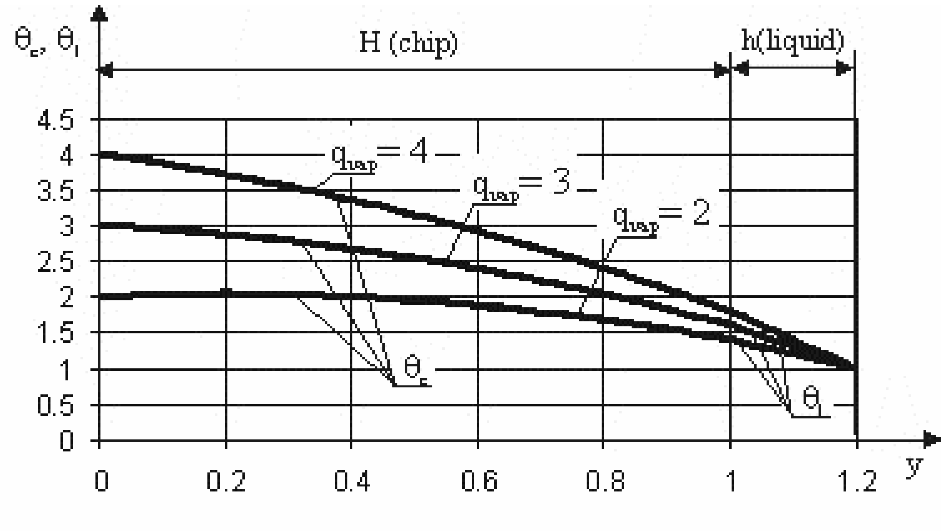


Fig. 4. Temperature distributions in the chip and in the liquid ($B_C = 2$, $\lambda = 0.8$, $\theta_\mathrm{b} = 1$).

Finally, an exact stationary solution of Eq. (3) can be expressed as

$$\begin{aligned}
&\theta_\mathrm{c} = \theta_\mathrm{b} - \frac{B_C}{2}\left(y^2+1\right) + \left(B_C - \tilde{\lambda}\cdot q_\mathrm{vap}\right)\cdot x + q_\mathrm{vap}(h+\tilde{\lambda}) \quad \text{for} \quad 0 \le y \le 1\,,\\
&\theta_\mathrm{l} = \theta_\mathrm{b} - q_\mathrm{vap}(y-1-h) \quad \text{for} \quad 1 \le y \le 1+h\,.
\end{aligned} \tag{5}$$

The above solutions in the graphical form are presented in Fig. 5. The influence of the volume of heat on the temperature distributions is evident. We can see that the simple theoretical model, which is presented here, gives interesting results. Utilization of the technical properties of the device to carry out the chilling process is very important here. The evaporation heat of the liquid is relatively large and, therefore, only a small flow of the liquid is sufficient to ensure high efficiency of cooling. In other words, no large flows are required to secure effective cooling and the driving power as well as the energy supplied does not have to be large.

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