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The calculating model of microstructured flat plate wettability during evaporation into the stagnation flow

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Abstract. The results of the analysis of the problem of wetting the microstructured flat wall surface during adiabatic liquid evaporation into a boundary layer of air flowing at right angles are presented. The basic conservation laws are formulated in the form of differential equations that allow calculating the velocity and height of liquid rise in capillaries, wetting dynamics, depth and mass of the liquid in capillaries, and the evaporation surface area.

1. Introduction

The development of modern technologies in the field of power and microelectronics, as well as high-performance microchips, powerful compact power keys and drivers with high heat release requires the creation of new methods for removing high heat fluxes [1, 2]. One of the possible approaches to solve the problem of heat removal from electronic components while maintaining or reducing the mass and dimensions of products is the use of capillary-porous coatings (modifications) of the heat exchange surface, which can provide passive supply of cooling liquid working fluid to the heat release areas due to capillary pressure. Various methods of creating micro-, nano-, and combined structured surfaces with the required properties have been developed; these are, for example, a porous structure [3], vertical micro-columns [4], open rectangular micro-channels [1, 3, 5], and sintered coatings [6].

To date, studies of heat and mass transfer on structured surfaces based on an array of open micro-channels [1, 3, 5] that have a high permeability to liquid, which leads to low viscous friction at a high heat flux removed by evaporation, are relevant. These modifications can be used to cool electronic components with a thermal load of more than 100 W/cm^2. Due to the high capillary pressure, micro-channel arrays can pump the working fluid over long distances at unprecedented velocities, even overcoming the force of gravity, which is due to the unique hierarchical absorption structure. It is found in [7] that the velocity of the working fluid through a vertically arranged structured glass sample can reach 3.8 cm/s.

It should be emphasized that the task of removing high heat fluxes from the high-temperature (heat-loaded) surfaces of the target products due to evaporation of the working fluid consists of two parts: the supply of the working fluid to the heat release area and the removal of steam from the heat exchange surface to the ambient medium. Progress in the development of efficient structured surfaces allows solving the first part of the problem. To solve the problem in its entirety, it is necessary to ensure sufficient convective heat and mass transfer on the modified surface under conditions of liquid evaporation and capillary wetting of a specific surface.

This paper presents a simple physical and mathematical model for calculating the dynamics of wetting of a microstructured flat wall during evaporation and entrainment of working fluid vapor into the boundary layer of air flowing over the wall at a right angle.

2. Problem statement

Figure 1 shows the problem statement and the main parameters of the problem. The dynamics of a liquid rising vertically along a semi-open capillary is considered. The liquid is a wetting agent for the base material. Let us assume that the liquid has constant temperature t_L and density ρ_L. The temperature of the liquid and the base material is assumed to be equal to the equilibrium temperature of the evaporation surface, and then we define it as the temperature of the liquid. Such conditions are implemented in special refrigeration units with feedback closed to the temperature of the evaporating liquid, which can be measured by thermocouples or IR receivers [8, 9]. The heat required for liquid evaporation is supplied only by convection from the air flow. Such conditions are commonly referred to as adiabatic evaporation. Similar conditions can be achieved by heating the air flow for the temperature of the evaporating liquid to correspond to the ambient temperature [10].

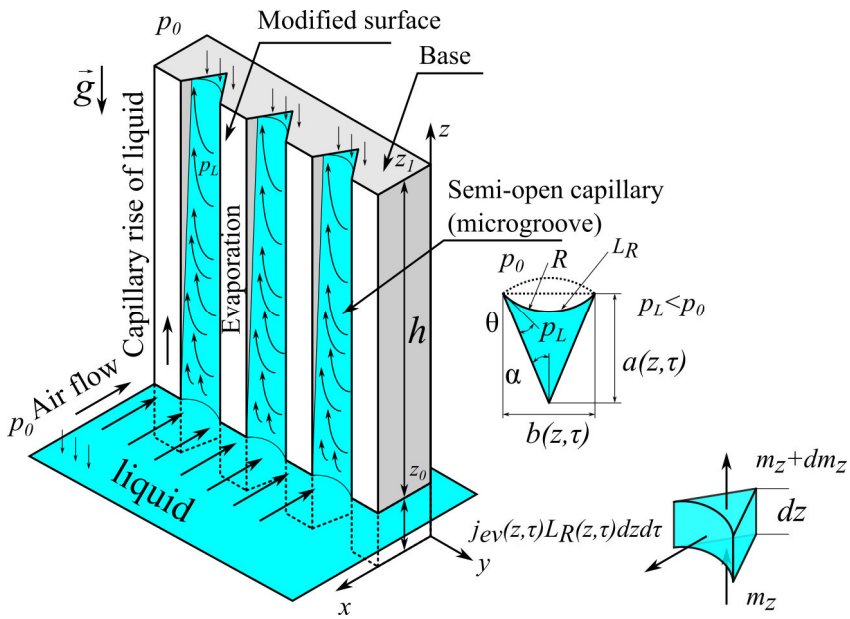

Figure 1. The scheme of liquid evaporation from a flat modified surface into the stagnation flow of air.

The origin of coordinates is associated with the lower face of the modified surface immersed in a tank of liquid. The immersion depth is z_0. At the initial time (at $\tau_0 = 0$) we assume that the liquid fills the capillaries only up to the level in the tank, which corresponds to the overlap of the cross-section of the capillaries by the removed partition. As the liquid rises through the capillaries, its level in the tank drops. However, we neglect the dynamics of the liquid level drop in the tank in the first approximation, considering that the tank capacity is large enough. We obtain the system of equations describing the rise of the liquid in the capillaries.

3. The differential equation of fluid dynamics in a single capillary

3.1 Capillary filling with liquid

For the elementary section of a single capillary in the projection on the vertical direction of the coordinate system we write the law of conservation of mass:

$$\frac{dm_z}{dz}dz + dm_x = 0 \tag{1}$$

The change in the mass of the liquid in the elementary volume occurs due to changes in the position of the meniscus over time and depending on the position of the elementary volume over the capillary height. Changing the position of the meniscus leads to a change in the cross-sectional area of the liquid $S(z,\tau)$ in the capillary and the area of contact between the liquid and air (the area of evaporation of the liquid $L_R(z,\tau)dz$). The intensity of liquid evaporation in general is $j_{ev}(z,\tau)$. Then from (1) it follows:

$$\rho_L \frac{d(Sw_z)}{dz} + j_{ev}L_R = 0 \tag{2}$$

In the first approximation, we assume that the velocity of the liquid along the capillary at each point along the height of the column of liquid is constant $w_z = f(\tau)$ and is determined in accordance with the law of conservation of momentum, then:

$$\frac{dS}{dz} = -\frac{j_{ev}}{\rho_L w_z}L_R \tag{3}$$

Let us take the shape of a single capillary in the form of a triangular groove with a depth $a(z,\tau)$ and width $b(z,\tau)$. We associate the change in the cross-sectional area of the liquid $S(z,\tau)$ and the length of the meniscus curve $L_R(z,\tau)$ with the depth of the capillary and the wetting angle θ, which for a given wall material and type of liquid is considered constant. $S = ab/2 - S_R$, where $S_R = \beta R^2$ is the area of the sector formed by the meniscus of the liquid. For the calculation, we assume that the vector of the surface tension force lies in the plane perpendicular to the axis z, then the radius of the meniscus can be calculated by the formula $R = b/(2\cos(\alpha+\theta))$, the half-opening angle of the sector β is related to the wetting angle θ and the half-opening angle of the groove α by the ratio $\alpha+\theta+\beta = \pi/2$. Eventually, $b = 2a \cdot tg\alpha$;

$$L_R(z,\tau) = 2\beta R = a \cdot \underbrace{\frac{2tg\alpha(\pi/2-(\alpha+\theta))}{\cos(\alpha+\theta)}}_{c_1}; \quad S(z,\tau) = a^2 \underbrace{tg\alpha\left(1-\frac{c_1}{2\cos(\alpha+\theta)}\right)}_{c_2}, \tag{4}$$

where c_1 and c_2 are the constants defined only by the wetting angle and the half-opening angle of the triangular groove. Let us substitute the obtained relations in equation (3):

$$a = a_0 - \frac{c_1}{2\rho_L w_z c_2}\int_{z_0}^{z} j_{ev}dz \tag{5}$$

The resulting expression determines the depth of the liquid column in a triangular capillary when the liquid moves along the capillary at a velocity $w_z(\tau)$ and evaporates with a mass flow rate $j_{ev}(z,\tau)$. The depth of the liquid at the boundary of the capillary with the liquid in the tank is a_0. It can be assumed that at this boundary, the liquid completely fills the triangular channel, and the depth of the liquid is equal to the depth of the channel.

3.2. Influence of the evaporation rate on the filling of the capillary with liquid

To determine the intensity of liquid evaporation from the capillary under conditions of exclusively convective heat supply from the incoming air flow (adiabatic evaporation conditions), we can write: $q_w = j_{ev}h_{ev}$, where h_{ev} is the latent heat of liquid vaporization at the equilibrium temperature of its

surface in the meniscus region. In the presence of an active thermal stabilization system, it can be assumed that the temperature of the liquid is the same throughout the entire volume of the capillary. In the future, we will talk about this temperature as the temperature of the liquid. The heat supplied to the liquid meniscus from the incoming air flow can be determined by the formula: $q_w = \rho_0 w_0 c_{p0}\left(T_0 - T_w\right) St_T$, where the Stanton number is determined depending on the mode of air flow along the modified surface and the angle of inclination of the surface to the incoming flow. With the vertical orientation of the plate and the laminar flow mode, neglecting the influence of the transverse vapor flow of the liquid that occurs during evaporation, we can write [11]:

$$St_T = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}} = \frac{1.14}{\sqrt{\mathrm{Re}}\,\mathrm{Pr}^{0.636}}, \tag{6}$$

where $\mathrm{Re} = \rho_0 w_0 L/\mu_0$ is the Reynolds number based on the velocity of the incoming air flow and the length of the modified section of the plate, and $\mathrm{Pr} = 0.7$ is the Prandtl number for air. As follows from the above relations, for the conditions under consideration, the evaporation intensity is constant along the length of the plate and is equal to

$$j_{ev} = 1.14 \cdot \frac{c_{p0}\mu_0}{h_{ev}} \frac{\sqrt{\mathrm{Re}}}{L\,\mathrm{Pr}^{0.636}}\left(T_0 - T_w\right) = const\,.$$

Then the expression (5) can be converted to the form:

$$a = a_0 - \frac{c_1}{2c_2}\frac{j_{ev}\left(z - z_0\right)}{\rho_L w_z} \tag{7}$$

3.3. The velocity and acceleration of liquid rise in a capillary

Let us determine the change in the height of a liquid column $h = z_1 - z_0$ over time: $\dot{h} = w_z$; $\ddot{h} = \dot{w}_z$ based on Newton's second law:

$$m\dot{w}_z = \sum_{i=1}^{n} F_{zi}\,.$$

The mass of the liquid contained in the capillary, depending on the height of the liquid column, can be determined as follows

$$m = c_2\rho_L \int_{z_0}^{z_1} a^2 dz = \rho_L c_2 a_0^2 h - \frac{c_1}{2} j_{ev}\frac{1}{w_z}\left(a_0 h^2 + \left(\frac{c_1}{6}\frac{j_{ev}}{c_2\rho_L}\frac{1}{w_z}\right)h^3\right) \tag{8}$$

The column of liquid in the capillary is affected by gravity, capillary pressure due to the curvature of the liquid-air interface, and the friction force when the liquid moves along the channel along the walls. In the first approximation, the friction force can be neglected, assuming that the velocity of the liquid is small. When the plate is vertically oriented, the force of gravity can be defined as $F_{z1} = -mg$. The “minus” sign determines the direction of the force against the positive direction of the coordinate z . The surface tension force is directed tangentially to the liquid-air interface and is determined by the formula: $\overrightarrow{F_2} = \sigma l_c$, where l_c is the length of the contact line. In contrast to closed capillaries, as the liquid rises along the semi-open capillary, the length of the contact line will change, both by changing

the meniscus geometry and by evaporation. In addition, the angle γ, whcih determines the projection of the surface tension force on the axis z will also change . We associate these values with the height of the liquid column in the capillary

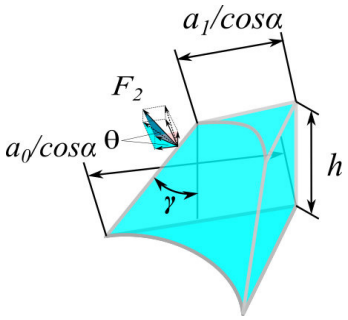

Figure 2. Determining the projection of the surface tension force on the axis z.

As follows from figure 2, $tg\gamma = (a_0 - a_1)/(h\cos\alpha)$; $l_c = 2h/\cos\gamma$. As a result, the projection of the surface tension force on the axis z: $F_{z2} = 2\sigma(a_0 - a_1)\cos\theta/\cos\alpha$. Write down the differential equation for determining the dynamics of the liquid column in the capillary, taking into account (7).

$$\left(\rho_L c_2 a_0^2 h - \frac{c_1}{2} j_{ev} \frac{1}{w_z}\left(a_0 h^2 + \left(\frac{c_1}{6}\frac{j_{ev}}{c_2\rho_L}\frac{1}{w_z}\right)h^3\right)\right)(\ddot{h} + g) = \frac{2\sigma\cos\theta}{\cos\alpha}\frac{c_1}{2c_2}\frac{j_{ev}h}{\rho_L w_z}. \quad (9)$$

Let us multiply the left and right parts of the equation by $\rho_L w_z^2 / c_2 h$, and taking into account $w_z = \dot{h}$ we get:

$$\boxed{\left(c_4^2\dot{h}^2 - c_3 c_4 h\dot{h} - c_3^2 h^2/3\right)(\ddot{h} + g) = c_3 c_5 \dot{h}}, \quad (10)$$

where: $c_3 = c_1 j_{ev}/2c_2^2$, $c_4 = \rho_L a_0$, $c_5 = 2\sigma cos\theta/cos\alpha$. Equation (10), supplemented by initial conditions for the position and velocity of the interface between air and liquid filling the capillary, allows solving the problem of wetting the modified surface when the liquid evaporates into the incoming air flow. The resulting equation is a rigid nonlinear ordinary second-order differential equation. To solve this problem, special, usually implicit numerical methods are required.

4. Conclusions

The analysis of the problem of wetting a modified surface of a flat wall during adiabatic evaporation of the liquid into a boundary layer of air running at a right angle has been carried out. The basic conservation laws are formulated in the form of differential equations that allow calculating the height of liquid rise in capillaries (10), wetting dynamics $\dot{h} = w_z$, $\ddot{h} = \dot{w}_z$, depth (7) and mass of liquid in capillaries (8), and the evaporation surface area (4). It is shown that the solution of the problem requires integration of a rigid nonlinear ordinary second-order differential equation.

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