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Peculiarities of heat transfer in a flat disk-shaped evaporator of a loop heat pipe

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ABSTRACT

Two models of a flat disk-shaped evaporator of a loop heat pipe have been developed for analyzing the effect of the convective component on heat transfer in a wick, and also on heat-exchange processes in an evaporation zone. Simulation data were obtained for two evaporators. The first evaporator was made entirely of copper, and the second had a body of stainless steel and a nickel wick. The geometrical dimensions of the evaporators were equal. The diameter of the heating zone was 30 mm. Calculations were made for heat fluxes from $2.8 \cdot 10^4$ to $4.2 \cdot 10^5$ W/m^2. Water was used as a working fluid. An analysis of the results has shown that the contribution of the convective component to the overall heat transfer is small. The higher the thermal conductivity of the wick, the smaller the effect that the convection has on the temperature distribution in the evaporator.

1. Introduction

At present porous materials are widely used in systems of penetrating cooling of heat-tensioned elements [1]. It is well known that the use of a liquid coolant in combination with evaporative heat exchange at the surface of a porous wall makes it possible to increase considerably the efficiency of such systems at the expense of intensification of heat-exchange processes, reduction of the flow rate of the working fluid, the expenditure of energy for its pumping, and also the improvement of mass-and-size characteristics of the whole system. The same approaches are used in such heat-transfer devices as heat pipes and loop heat pipes (LHPs). In addition to this, their capillary-porous structure (or wick) functions as a capillary pump providing the pumping of a working fluid on a closed cycle with liquid–vapor (in the zone of heat supply) and vapor–liquid (in the zone of heat removal) phase transitions [2]. In loop heat pipes (Fig. 1), as distinct from conventional heat pipes, the wick is only in the heat supply zone [3]. To remove vapor which forms during the liquid evaporation from the wick menisci, a ramified system of vapor-removal grooves is provided here. In LHPs with disk-shaped [4–6] and cylindrical evaporators the flows of heat and cooling liquid are mainly directed towards each other (Fig. 2).

The LHP operating characteristics depend to a large degree on the processes of heat-and-mass transfer in the evaporator and the temperature distribution in it. There are quite a number of papers developed to theoretical investigations of this topical problem, which present different approaches to simulation of the evaporator thermal state. Some of them take into account convection in heat transfer through a porous material [7–9]. In others it is assumed that the main mechanism of heat transfer in a wetted wick is thermal conductivity, and the convective component is insignificant owing to the small flow rate of the working fluid in an LHP and, consequently may be neglected [10–13]. At the same time, the question of the effect of a cold liquid moving through the wick on the temperature distribution in the evaporator is still open.

The present paper gives a comparative analysis of the results of numerical simulation of temperature distribution in a disk-shaped evaporator at convective heat transfer in conditions of a one-phase flow of a coolant through the wick, and also in conditions at which the main mechanism of heat transfer in the wick is its effective thermal conductivity.

2. Geometrical model and formulation of the problem

The scheme of a typical fragment of an LHP disk-shaped evaporator is presented in Fig. 2. Heat is supplied to one of the flat surfaces of the evaporator, which is in contact with the wick. Located here are vapor-removal grooves, which have a rectangular cross-section. The wick ledges located between two neighboring

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Nomenclature

c_p	heat capacity (J/kg K)
d	diameter (m)
h_v	latent heat of vaporization (J/kg)
H	thickness (m)
k	thermal conductivity (W/m K)
l	length (m)
$\dot{m}$	fluid mass flow rate (kg/s)
Q_{load}	heat load (W)
Pe^*	modified Péclet number
S	surface, area (m^2)
$S_\perp$	cross-section area (m^2)
T	temperature (°C)
x	axis coordinate (m)
X	dimensionless coordinate
w	velocity (m/s)

Greek symbols

α	heat exchange coefficient (W/m^2 K)
ρ	density (kg/m^3)
θ	dimensionless temperature
Γ	boundary

Subscripts and superscripts

body	evaporator body (or case)
c	condenser
cc	compensation chamber
cool	cooling
l	liquid
s	saturation
v	vapor
vg	vapor removal groove

vapor-removal grooves ensure a thermal contact between the body and the porous material. The wick is saturated with liquid. Most of the heat supplied to the evaporator goes into the liquid evaporation from the surface of the menisci facing the vapor-removal grooves. With their help the vapor generated is removed from the evaporator, moving along the vapor line into the condenser (Fig. 1). Here it condenses giving up heat to an external heat sink. The cold liquid returns into the evaporator through the liquid line, first finding its way into the compensation chamber (CC), and from there into the wick. As the liquid moves through the porous material to the evaporation zone, it heats up at the expense the opposite heat flow, which moves from the heating zone to the cold compensation chamber. Flat evaporators in which such a scheme of motion of heat and working-fluid flows is realized belong to “evaporators with opposite replenishment” (EOR) [14].

The aim of the present work was analyzing the effect of the convective component of heat transfer on the evaporator thermal state and heat-exchange processes in the evaporation zone. To simulate thermal processes in the evaporator, use was made of two disk-shaped evaporators with equal geometrical dimensions, but different heat-conducting properties of their structural materials. The first had a body of a stainless steel with a thermal conductivity k_{ss} = 17 W/m K and a nickel wick with an effective thermal conductivity k_{Ni} = 4 W/m K. The second had a copper body with a thermal conductivity k_{Cu} = 380 W/m K and a copper wick with an effective thermal conductivity k_{Cu} = 40 W/m K. The main geometrical parameters of these evaporators are presented in Table 1. Water was used as a working fluid both in the SS–Ni evaporator and the Cu–Cu evaporator.

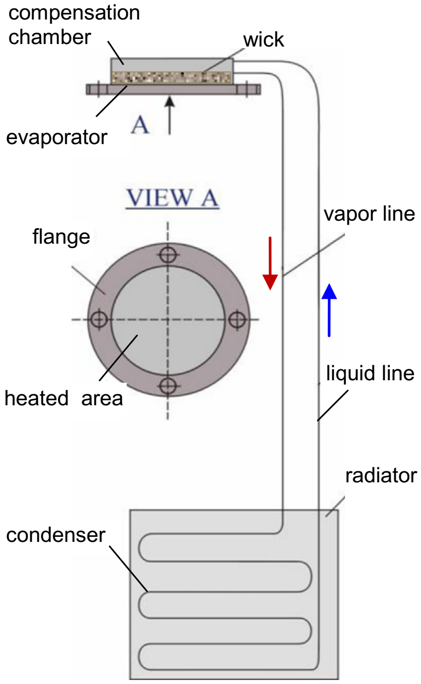

Fig. 1. Scheme of a loop heat pipe with a flat disk-shaped evaporator.

3. Mathematical formulation

For simulating heat transfer in a flat disk-shaped LHP evaporator use was made of the following assumptions.

1. The problem is stationary and one-dimensional.
2. The wick pores are filled with liquid. The local values of the temperatures of the liquid and the porous material are equal.
3. The flow rate of the working fluid is determined by the quantity of heat expended in the liquid evaporation.
4. The heat and liquid flows in the evaporator are directed towards each other.
5. The temperature of the saturated vapor in the vapor-removal grooves is constant, T_v = const.
6. The temperature of the cold water that comes from the condenser into the evaporator is constant, T_{cool} = const, and independent of the flow rate of the working fluid. One can observe a uniform temperature distribution in the compensation chamber.
7. The liquid flow conditions in the wick are laminar and stable.
8. The edge effects of a macroobject, i.e. an evaporator, appear only slightly and are neglected.

3.1. Governing equations

The heat conduction equation for the evaporator body is

$$\frac{\partial^2 T}{\partial x^2} = 0. \tag{1}$$

The energy equation for the wick is

$$\frac{k_{wick}}{\rho_l \cdot c_p} \cdot \frac{\partial^2 T}{\partial x^2} = w_x \cdot \frac{\partial T}{\partial x}, \tag{2}$$