HEAT-TRANSFER RATE IN THE CONDENSER SECTION OF A HEAT PIPE

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A dimensionless equation for calculation of the heat-transfer rate in the condenser of a heat pipe is derived on the basis of dimensional analyses of the fundamental convective heat-transfer equations. The experimental results are generalized.

According to the operating principle of a heat pipe its heat-transporting capability is determined by the hydrodynamics of the vapor and liquid flows as well as by the radial heat-transfer rate in the vaporizer and condenser, and the latter rate determines the temperature drop over the length of the pipe [1]. Besides the external heat-transfer conditions, the value of that temperature drop is also affected by the heat resistance of the pipe casing, the thermal conductivity of the wet wick, the temperature changes in phase transitions, etc.

Whereas in the vaporization regime of the heat pipe its performance characteristics can be calculated in the interval of moderate vapor pressures on the basis of a simple model taking into account only the thermal conductivity of the wet wick [2], in the boiling regime and at low vapor pressures the problem is greatly complicated by the enhanced role of the heat-transfer rate between the moving vapor and the liquid at the phase interface.

We consider the heat-transfer process in a heat pipe condenser, using the fundamental convective heat-transfer equations.

We assume that the motion of the liquid in the wick is one-dimensional and can be described by the Darcy relation for liquid flow in porous materials, whereupon the equations of motion, energy, and continuity for the condenser assume the form

$$-\frac{dP_v}{dz}+2\sigma\frac{d}{dz}\left[\frac{1}{R_{cap}(z)}\right]+\frac{\mu_L}{K\rho_L}\left[\rho_L W_L(z)\right]=\frac{1}{2\rho_L}\cdot\frac{d}{dz}\left[\left|\rho_L W_L(z)\right|^2\right]. \tag{1}$$

$$i_L\frac{d}{dz}\left[\rho_L W_L(z)\right]+\frac{Q}{\varepsilon F_W L_c}=\frac{\pi d_v}{\varepsilon F_W}i_v G_v, \tag{2}$$

$$W_v\frac{\pi d_\pi^2}{4}\rho_v=W_L\varepsilon F_W\rho_L. \tag{3}$$

We reduce these equations to dimensionless form. We adopt as the reference dimension the radius of the vapor space, and as the reference velocity the vapor velocity at the interface between the two phases. Then

$$W'_L=\frac{W_L}{U_w}=\frac{\alpha(\bar{t}_L-t_{st}^c)F_c^2\rho_v}{rW_L(\rho_L\varepsilon F_W)^2},$$
$$R'_{cap}=\frac{R_{cap}}{R_v};\quad z'=\frac{z}{R_v}. \tag{4}$$

Substituting expressions (4) into Eqs. (1), (2), and (3) and grouping the parameters into dimensionless complexes, we find that the heat transfer in the heat pipe condenser depends on the following factors:

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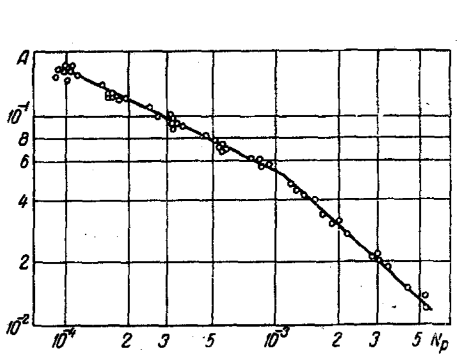

Fig. 1

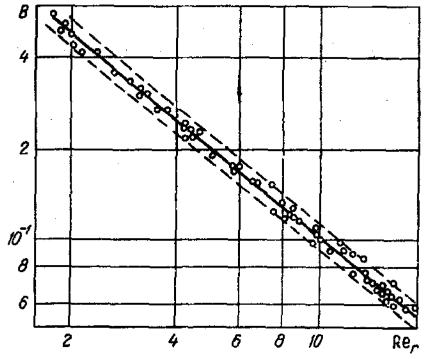

Fig. 2

Fig. 1. Influence of vapor pressure on heat-transfer rate in heat pipe condenser. $L = 470$ mm; $L_c = 100$ mm; $d = 19.5$ mm; $A = StRe_2/CK^{0.4}Pr^{1.3}$.

Fig. 2. Generalized experimental data on heat-transfer in heat pipe condenser. $L = 470$ mm; $L_c = 100$ mm; $d = 19.5$ mm; $B = StN_p^n/CK^{0.4}Pr^{1.3}$, where $n = 0.833$ for $N_p > 1.1 \cdot 10^{-3}$ and $n = 0.48$ for $N_p < 1.1 \cdot 10^{-3}$.

$$St = f\left(Re_r;\ N_p;\ K;\ Pr_L;\ \frac{R_{cap}}{R_v};\ \frac{R_v}{k};\ \frac{F_c}{\varepsilon F_w}\right), \tag{5}$$

where $Re_r = R_v U_w/\nu_v$ is the Reynolds number, $N_p = m\sigma/P_v R_v$ is a dimensionless complex characterizing the ratio of the surface tension forces and pressure forces, m is the form factor of the liquid meniscus, $K = [r/c_{p_L}(\bar{t}_L - t_{st}^c)]$ is the Kutateladze number, $St = a/c_{p_L}\rho_L W_L$ is the Stanton number, $Pr_L = \nu_L/a$ is the Prandtl number, and $\alpha = [Q/F_c(\bar{t}_L - t_{st}^c)]$ is the heat-transfer coefficient in the condenser.

An analysis of expression (5) shows that the heat transfer in the condenser is affected by the thermal power transported by the pipe, the vapor pressure at which that power is transported, the physical properties of the working liquid, and the geometry of the heat pipe and wick.

On the basis of a generalization of the experimental data on heat-transfer in heat pipe condensers with water and alcohol as the heat-transfer agents we obtain the following equation relating the dimensionless complexes involved in Eq. (5):

$$St\,N_p^n\,Re_r = CK^{0.4}\,Pr^{1.3}, \tag{6}$$

where $n = 0.48$ for $N_p < 1.1 \cdot 10^{-3}$ and $n = 0.833$ for $N_p > 1.1 \cdot 10^{-3}$, and C is a constant including the geometrical characteristics of the heat pipe and wick, from (5). The physical constants of the working liquid were determined for the calculation of the criteria from the midpoint between the vapor temperature and the temperature of the consenser wall. The heat of vaporization and surface tension of the liquid were determined from the vapor temperature.

The influence of the vapor pressure on the heat-transfer rate in the condenser is shown in Fig. 1.

As the figure indicates, the heat-transfer rate in the condenser changes abruptly for $N_p = 1.1 \cdot 10^{-3}$, which corresponds to a vapor pressure of $0.11 \cdot 10^5$ N/m². This change is elicited by the fact that as the vapor pressure is reduced the vapor condensation coefficient decreases and the heat resistance of the phase transition increases:

$$R_W = \frac{t_v - t_{sur}}{q},$$

where

$$q = \frac{Q}{\pi d_v L_c}. \tag{7}$$

Figure 2 gives generalized experimental data on the heat transfer in the condenser of a heat pipe with a diameter of 19.5/0.25 mm. The total length of the pipe is 470 mm, and length of the condenser is 100 mm, and the diameter of the vapor duct is 17.7 mm.

The wick, which is composed of three layers of brass screen with a mesh of 0.2 mm, has a thickness of 0.65 mm and a permeability of $2.02 \cdot 10^{-10}$ mm.

The solid line in Fig. 2 corresponds to Eq. (6), and the dashed curves delimit the interval in which the deviation of the experimental data from the analytical dependence does not exceed 20%.

NOTATION

P is the pressure, N/m^2;
σ is the surface tension, N/m;
z is the axial coordinate, m;
R is the radius;
μ is the viscosity, $N \cdot sec/m^2$;
k is the permeability, m^2;
ρ is the density, kg/m^3;
W is the axial velocity, m/sec;
i is the enthalpy, J/kg;
ε is the porosity;
F is the area, m^2;
L is the length, m;
G is the mass flow rate across unit area, kg/m^2sec;
r is the heat of vaporization, J/kg;
c_p is the specific heat, $J/kg \cdot °C$;
t is the temperature, °C;
Q is the heat flux, W;
U is the radial velocity, m/sec;
d is the diameter.

Subscripts and Superscripts

L refers to the liquid;
v refers to the vapor;
sur refers to the surface;
W refers to the wick;
cap refers to the capillary;
c refers to the condenser;
w refers to the liquid—vapor interface.

LITERATURE CITED

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