EFFECT OF THERMAL LOAD ON HEAT-TRANSFER COEFFICIENT IN POROUS-SUBLIMATION COOLING

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It was shown that, under thermal loads that are sufficiently larger (smaller) than a certain value, the heat transfer coefficient for porous-sublimation cooling increases (decreases) with an increase in the thermal load.

During porous-sublimation cooling (PSC) [1-6], heat is removed from the cooled surface (see Fig. 1) through the porous skeleton and is transferred to a solid refrigerant located in the pores. The vapor formed at the sublimation front moves through the pores to the surface from which the vapor is evacuated, and the front moves toward the cooled surface [1, 4].

In comparison with other methods of sublimation cooling [7, 8], PSC considerably improves the heat transfer between the cooled object and the refrigerant [2, 4, 5]. In addition, in contrast to contact sublimation, porous-sublimation cooling does not require mechanical devices to press the solid refrigerant to the cooled surface, thus making it possible to sufficiently simplify the design of sublimation systems and to improve their reliability.

Heat transfer efficiency in sublimation cooling is characterized by the heat transfer coefficient [4, 7, 8]

$$\alpha_0 = q_0/(T_0 - T_L), \tag{1}$$

where $T_L = T_s(P_L)$. In the case of contact sublimation, α_0 increases with an increase in q_0 [7, 8]. The same effect of q_0 on α_0 has been observed in experiments on PSC [2, 5]. We will show that in PSC the coefficient α_0 grows with an increase in q_0 only for sufficiently large q_0, whereas for small q_0 the value of α_0 should decrease as q_0 increases.

Substituting the expressions [2, 4]

$$T_0 = T_l + q_0 l/\lambda_c,\ T_l = 2\omega \ln^{-1}(\delta^2/W),\ W = P_L^2 + 2q_0\theta_L(L-l)/(\omega k_c), \tag{2}$$

$$l = L - q_0 t/(\rho \varepsilon_c \varepsilon_S \gamma),\ \omega = \gamma\mu/R,\ \theta_L = T_L \eta(T_L),\ \delta,\ \lambda_c = \text{const} \tag{3}$$

into (1) and using for the saturated pressure the pressure relation [7]

$$P_s(T) = \delta \exp(-\omega/T), \tag{4}$$

we can show that, for time-independent q_0 and P_L, the sign of the derivative $\partial\alpha_0/\partial q_0$ coincides with the sign of the quantity

$$J = \sigma\beta_l^2\{\exp[2(\beta_L - \beta_l)] - 1\} + \beta_L\{\beta_l + \exp[2(\beta_l - \beta_L)] - 1\} - \beta_l^2, \tag{5}$$

where

$$\sigma = \frac{k_c P_L^2 \beta_L}{2\theta_L \lambda_c},\ \beta_L = \frac{\omega}{T_L},\ \beta_l = \frac{\omega}{T_l}.$$

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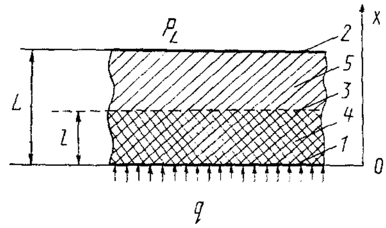

Fig. 1. Sketch of sublimational cold accumulator with heat conducting porous skeleton: 1) cooled surface; 2) evacuation surface for the solid refrigerant vapors; 3) sublimation front of the solid refrigerant; 4) region containing the solid refrigerant; 5) region not containing the solid refrigerant.

If P_L, q_0 = const, then $T_l = T_l[l(t)]$ (see (2), (3)), while the quantities T_L, β_L, and σ are constant. In this case, the quantities β_l, J, α_0, $\partial\alpha_0/\partial q_0$ can be considered to be the functions of the variable $H = L - l(t)$, where $H = H(t)$ is the distance between the sublimation front and the vapor evacuation surface. Note that $T_l \geq T_L$ (see (2)-(4)), i.e., $\beta_L \geq \beta_l$, and the value of H grows in the porous-sublimation cooling process and, at any q_0, varies from 0 up to L. From (2)-(4) we find

$$\exp[2(\beta_L - \beta_l)] = 1 + \frac{H}{L}\frac{q_0}{q_*}, \tag{6}$$

where

$$q_* = \frac{\omega k_c P_L^2}{2\theta_L L}. \tag{7}$$

At the initial stage of cooling when $H/L \ll q_*/q_0$, from (6) we have $\beta_L - \beta_l \ll 1$, i.e., the exponential functions in (5) can be expanded into a series in powers of $\beta_L - \beta_l$ and, with accuracy up to order $(\beta_L - \beta_l)^2$, we obtain

$$J = (\beta_L - \beta_l)(2\sigma\beta_l^2 + \beta_l - 2\beta_L). \tag{8}$$

Since $\beta_L \geq \beta_l$, the sign of J in (8) is determined by the sign of the quadratic trinomial

$$V(\beta_l) = 2\sigma\beta_l^2 + \beta_l - 2\beta_L.$$

Clearly, this trinomial has two real roots, and of the curve $V = V(\beta_l)$ is convex downwards, while $V(0) = -2\beta L < 0$; $V(\beta_L) = \beta_L(2\sigma\beta_L - 1) \leq 0$, since $2\sigma\beta_L \leq 1$ (the latter inequality follows from the condition of stability of the planar form of the sublimation front [3, 4] $P_s^2(T_l) \leq (\lambda_c k_c)(T_L/\omega)^2\theta_L$ at $T_l = T_L$). Therefore, the roots of the trinomial $V(\beta_l)$ satisfy the conditions $\beta_l^{(1)} < 0$, $\beta_l(2) \geq \beta_L$, and the trinomial $V(\beta_l)$ itself is negative for $0 < \beta_l < \beta_L$. Thus, at the initial stage of cooling, when $H/L \ll q_*/q_0$, we have $J < 0$, that is, $\partial\alpha_0/\partial q_0 < 0$, and the heat transfer coefficient α_0 falls with an increase in the thermal load q_0.

If $q_0 \ll q_*$ (small loads), then $Hq_0/(Lq_*) \ll 1$ for any H, since $H \leq L$. In this case, from (6) it follows that $\beta_L - \beta_l \ll 1$ throughout the whole cooling process, i.e., relation (8) and the condition $\partial\alpha 0/\partial q_0 < 0$ are valid for any H. Therefore, under small thermal loads, when $q_0 \ll q_*$, the heat transfer coefficient α_0 decreases with an increase in the load q_0.

Consider the case of large thermal loads, when $q_0 \gg q_*$. In this case, $q_0/q_* \gg 1$, and from (6) it follows that $\beta_L - \beta_l < 1$ only at the beginning of the cooling process when $H/L \ll 1$. Thus, for most of the cooling period, we have $\beta L - \beta_l \gg 1$. At the same time, $\exp[2(\beta L - \beta_l)] \gg 1$, $\exp[2(\beta_l - \beta_L)] \ll 1$, and from (5) we obtain

$$J \approx \sigma\beta_l^2 \exp[2(\beta_L - \beta_l)] + \beta_L(\beta_l - 1) - \beta_l^2. \quad (9)$$

Provided that $\beta_l = \omega/T_l \gg \omega/T_{tr} \gg 1$ (see [2, 4]), in (9) we can disregard unity in comparison to β_l, and, taking into account $\beta_L \geq \beta_l$, we obtain $J > 0$. Thus, under large thermal loads, when $q_0 \gg q_*$, for the greater part of the cooling period the condition $\partial\alpha_0/\partial q_0 0$ is satisfied, i.e., the heat transfer coefficient α_0 increases with an increase in the thermal load q_0.

As is shown above, independently of the relation between q_0 and q_*, at the beginning of sublimation when $H \to 0$, the condition $\partial\alpha_0/\partial q_0 < 0$ is fulfilled. In connection with this, let us present a sufficient condition for the positiveness of the quantity $\partial\alpha_0/\partial q_0$. Using (1)-(4), (7), we can show that the sign of $\partial\alpha_0/\partial q_0$ coincides with the sign of the expression

$$\frac{Hq_0}{\lambda_c} + T_l\left[1 - \frac{T_l}{\omega}\frac{\Gamma}{(1+\Gamma)}\right] - T_L, \quad (10)$$

where $\Gamma = Hq_0/(Lq_*) \geq 0$. It is obvious that $Hq_0/\lambda_c \geq 0$, $T_l/\omega \leq T_{tr}/\omega$, $\Gamma/(1 + \Gamma) \leq 1$. Thus, expression (10) is positive if

$$T_l\left(1 - \frac{T_{tr}}{\omega}\right) - T_L > 0,$$

from which, using (2)-(4), we find that the sufficient condition for $\partial\alpha_0/\partial q_0$ being positive has the form $t > t_*$, where

$$t_* = \tau\frac{q_*}{q_0}\left[\left(\frac{\delta}{P_L}\right)^{2T_{tr}/\omega} - 1\right], \quad (11)$$

and t is the time elapsed since the cooling began and τ is the total cooling time ($l(\tau) = 0$).

CONCLUSIONS

1. An equation was obtained [Eq. (7)] for the critical thermal load q_*, characterizing the dependence of the heat transfer coefficient α_0 on the thermal load q_0 in porous-sublimation cooling.

2. For $q_0 \ll q_*$, an increase in the thermal load q_0 is accompanied by a decrease in α_0; however, for $q_0 \gg q_*$, α_0 increases with an increase in q_0 during the greater part of the cooling period.

3. At the beginning of the process, when the time of cooling $t \to 0$, the coefficient α_0 falls with an increase in q_0 independently of the relationship between q_0 and q_*.

4. If $q_0 \gtrsim q_*$, the sufficient condition for the increase in α_0 with an increase in q_0 has the form $t > t_*$, where t_* is defined by Eq. (11).

NOTATION

α, heat transfer coefficient; q, heat flux density; T, temperature; P, pressure; t, time; l, coordinate of the sublimation front; λ, thermal conductivity; L, thickness of the porous solid; k, permeability; γ, specific heat of sublimation; μ, molecular weight of the refrigerant; R, universal gas constant; η, coefficient of the dynamic viscosity of refrigerant vapors; ρ, density of the solid refrigerant; ε, porosity; ε_S, fraction of pore space occupied by the solid refrigerant; H, distance between the sublimation front and the vapor evacuation surface; τ, time of the complete sublimation of the refrigerant. Indices: 0, surface being cooled; L, vapor evacuation surface; s, saturated state of the solid and gaseous phases of the refrigerant; c, porous skeleton; l, sublimation front; tr, triple point.

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