mining the fuel concentration and the total error of determining the model parameters; $1/\phi$, mean relative diameter of a hot particle. Dimensionless numbers: $\mathrm{Nu}=\alpha d_i/\lambda$; $\mathrm{Sh}=\beta d_i/D$; $\mathrm{Fr}=(U-U_0)^2/gH$; $\mathrm{Sc}=\nu/D$; $\mathrm{Ar}=\frac{gd_i^3}{\nu^2}\frac{\rho_i-\rho}{\rho}$.

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CHOICE AND OPTIMIZATION OF THE PARAMETERS OF A POROUS-SUBLIMATION COOLER

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The parameters of a porous-sublimation cooler (PSC) such that the temperature of the cooling surface a) does not exceed a prescribed value, b) is minimum, and c) does not exceed a prescribed value with minimum mass of the PSC are determined.

In the process of porous-sublimation cooling [1-3] heat is removed from the surface being cooled (Fig. 1) along a porous framework and is transferred to a solid refrigerant residing in the pores of the framework; this process results in sublimation of the refrigerant. Compared with other methods of sublimation cooling [4] a PSC substantially simplifies the construction of the cryosublimation systems, increases their reliability, and significantly improves heat transfer between the object being cooled and the refrigerant [2, 5]. When cryogenic systems are cooled it is usually necessary to choose the parameters of the PSC so that the temperature of the surface being cooled is minimum or does not exceed a prescribed value. For space cryogenic technology it is especially important to provide these conditions with minimum mass of the PSC.

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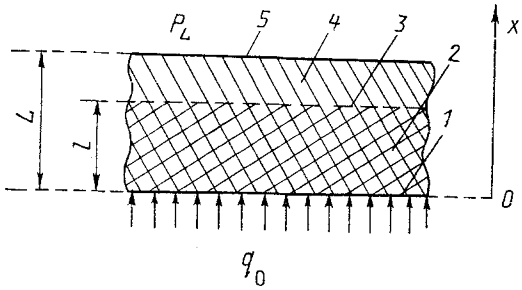

Fig. 1. Diagram of a porous-sublimation cooler: 1) the surface being cooled; 2) region containing the solid refrigerant (SR); 3) sublimation front of SR; 4) region not containing SR; 5) surface from which the vapor of the SR is evacuated.

1. Choice of Parameters of PSC with an Irregular Porous Structure. Let the heat flux density q_0 be given on the cooled surface of the PSC (Fig. 1) and let the pressure P_L on the vapor evacuation surface be known. We are required to choose the parameters L, λ_c, k_c, and ε_c so that over the time τ the temperature T_0 of the surface being cooled does not exceed a prescribed value T_m.

We shall assume that q_0 and P_L are constant. Then we have [2]

$$T_0 = T_0(l) = T_l(l) + q_0 l/\lambda_c, \tag{1}$$

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

$$l = l(t) = L - q_0 t/(\rho_1 \varepsilon_c \varepsilon_T \gamma), \tag{3}$$

where $\omega = \gamma\mu/R_g$; $\Psi_L = \Psi(T_L)$; $\Psi(T) = T\eta_2(T)$; $T_L = T_s(P_L)$; $\delta = \text{const}$ is the parameter in the relation [4]

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

The expressions (1)-(3) are valid, if the following condition for the sublimation front to remain flat during the process of porous-sublimation cooling is satisfied [1, 3]:

$$P_s^2(T_l) \leqslant \varphi_L \lambda_c/k_c, \text{ where } \varphi_L = \varphi(T_L) \approx \varphi(T_l),\ \varphi(T) = \Psi(T)(T/\omega)^2. \tag{5}$$

Taking into account the fact that $l(\tau) = 0$, from Eq. (3) we obtain

$$L = q_0\tau/(\rho_1 \varepsilon_c \varepsilon_T \gamma). \tag{6}$$

Since $P'_s(T) > 0$, in order for the condition (5) to be satisfied it is necessary and sufficient that it be satisfied for $T_l = \max T_l$. From Eqs. (2), (3), and (6) we have

$$\max T_l = 2\omega \ln^{-1}\left(\frac{\delta^2}{P_L^2 + A/H}\right), \tag{7}$$

where $A = 2q_0^2\tau\Psi_L/(\omega\rho_1\varepsilon_T\gamma)$ and $H = \varepsilon_c k_c$. Substituting $T_l = \max T_l$ into Eq. (5) and taking into account (4) we find

$$\lambda_c \geqslant K_c(P_L^2 + A/H)/\varphi_L. \tag{8}$$

Let the relation (8) and therefore also the relation (5) be satisfied. Differentiating Eq. (1) with respect to l and taking into account Eqs. (2), (4), and (5) we obtain

$$T_0'(l) = [P_s^2(T_l) - \varphi_L\lambda_c/K_c]\, q_0/[\lambda_c P_s^2(T_l)] \leqslant 0.$$

Thus if the sublimation front remains flat, then the temperature of the surface being cooled increases as l decreases (as t increases), and vice versa. Thus, $\max T_0 = T_0|_{l=0} = T_l|_{l=0} = \max T_l$ (see Eqs. (1) and (2)), and from Eqs. (4) and (7) we find $\max T_0 \leq T_m$ with

$$H \geqslant A/(P_m^2 - P_L^2), \tag{9}$$

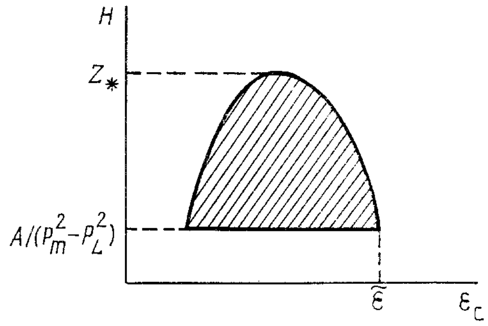

Fig. 2. The form of the region of values of $H = \varepsilon_c k_c$ that satisfy the conditions (9) and (13).

where $P_m = P_s(T_m)$. Thus if the parameters L, λ_c, k_c, ε_c satisfy the relations (6), (8), and (9), then the temperature of the surface being cooled does not exceed the value T_m.

2. Optimization of the Parameters of Plate-Type and Tubular PSC. We shall study a plate-type PSC with a framework consisting of parallel plates of thickness a. The spacing between the plates is equal to h; the surfaces of the plates are perpendicular to the surface being cooled. The parameters a and h must be chosen so that the flat sublimation front is stable and

2.1) the maximum (over the time τ) temperature of the cooled surface is minimum and

2.2) the mass of the PSC is minimum and the temperature of the cooled surface does not exceed the value T_m.

It is obvious that for plate-type PSC

$$\lambda_c = (1 - \varepsilon_c)\lambda_3, \tag{10}$$

$$\varepsilon_c = h/(a+h). \tag{11}$$

As estimates show [3], the flow of vapor between the plates of the PSC is usually laminar and in this case

$$k_c = h^3/[12(a+h)]. \tag{12}$$

We shall perform the optimization according to the criterion 2.1. Substituting Eq. (10) into Eq. (8), we obtain the condition under which the sublimation front remains flat in the form

$$H \leqslant Z(\varepsilon_c), \tag{13}$$

where $Z(\varepsilon_c) = [\varepsilon_c(1-\varepsilon_c)\lambda_3\varphi_L - A]P_L^2$. Since $H \geq 0$ and the quadratic polynomial $Z(\varepsilon_c)$ is nonnegative only for

$$\lambda_3 \geqslant 4A/\varphi_L, \tag{14}$$

the relation (14) is the necessary condition for the flat front to be stable. Let the condition of stability (13) be satisfied. Then max T_0 = max T_ℓ (see Sec. 1), and in addition max T_ℓ decreases as H increases (see Eq. (7)). Therefore, in order to solve the optimization problem under the criterion 2.1 it is sufficient to find the parameters $a = a_*$ and $h = h_*$ for which H(a, h) is maximum under the condition (13). It is obvious that the equality in Eq. (13) corresponds to the parameters a_* and h_*, and the function $Z(\varepsilon_c)$ at the point $\varepsilon_c = \varepsilon_c^* = 0.5$ assumes its maximum value

$$Z_* = (\lambda_3\varphi_L 4A)/(4P_L^2). \tag{15}$$

For this reason, taking into account Eqs. (11) and (12) we obtain

$$h_*/(a_* + h_*) = \varepsilon_c^* = 0.5,\ h_*^4/[12(a_* + h_*)^2] = \varepsilon_c^* k_c^* = Z_*.$$

Solving these equations for a_* and h_* we obtain

$$a_* = h_* = \sqrt{48Z_*}. \tag{16}$$

Since $\max T_0 = \max T_\ell$, substituting $H = \max H = Z_*$ into (7) and taking into account (4) and (15) we find

$$\min(\max T_0) = T_L\left[1 - \frac{T_L}{2\omega}\ln\left(\frac{\lambda_3\varphi_L}{\lambda_3\varphi_L - 4A}\right)\right]^{-1}. \tag{17}$$

Thus the optimal, in accordance with the criterion 2.1, parameters of a plate-type PSC are given by the formula (16), and the minimum value of the highest (over the time τ) temperature of the surface being cooled is determined from Eq. (17). The parameters of a PSC with a tubular structure in the form of parallel cylindrical capillaries in a continuous matrix are optimized in an analogous manner. For this case the relations (10), (13)-(15), and (17) are also valid and, using instead of Eqs. (11) and (12) the relations $\varepsilon_c = \pi R^2 n$, $k_c = \pi R^4 n/8$ [3], we obtain

$$R_* = \sqrt{32Z_*},\ n_* = 1/(2\pi R_*^2).$$

We now perform the optimization in accordance with the criterion 2.2. Since $M_1 = q_0\tau/\gamma = \text{const}$, it is sufficient to minimize the mass M_c, which, taking into account Eq. (6), is equal to

$$M_c = \rho_3 q_0 \tau (1 - \varepsilon_c)/(\varepsilon_c \rho_1 \varepsilon_T \gamma). \tag{18}$$

It is obvious that M_c decreases as ε_c increases, and in addition $\max T_0 \le T_m$ under the condition (9), and the flat front is stable under the condition (13). For this reason, in order to optimize under the criterion 2.2 it is sufficient to find the highest value of ε_c for which the conditions (9) and (13) are satisfied. It is obvious that these conditions are satis-satisfied only if $\max Z = Z_* \ge A/(P_m^2 - P_L^2)$, whence taking into account Eq. (15) we find

$$\lambda_3 \geqslant 4AP_m^2/[\varphi_L(P_m^2 - P_L^2)]. \tag{19}$$

If Eq. (19) is satisfied, then $Z(\varepsilon_c) = A/(P_m^2 - P_L^2)$ has two positive, roots, the largest of which is

$$\tilde{\varepsilon} = \{\lambda_3\varphi_L + [(\lambda_3\varphi_L)^2 - 4\lambda_3\varphi_L AP_m^2/(P_m^2 - P_L^2)]^{0.5}\}/(2\lambda_3\varphi_L).$$

For this case the range of values of H which satisfy the conditions (9) and (13) is shown in Fig. 2 (hatched region), whence one can see that the highest value of ε_c for which H belongs to the indicated region is $\varepsilon_c = \tilde{\varepsilon}$, and in addition $Z(\tilde{\varepsilon}) = A/(P_m^2 - P_L^2) = H(\tilde{a}, \tilde{h})$, where $\tilde{a}$ and $\tilde{h}$ are the optimal, under the criterion 2.2, values of a and h. Therefore, taking into account Eqs. (11) and (12), we obtain for a plate-type PSC

$$\tilde{h}/(\tilde{a} + \tilde{h}) = \tilde{\varepsilon},\ \tilde{\varepsilon}\tilde{h}^3 = [12(\tilde{a} + \tilde{h})] = A/(P_m^2 - P_L^2).$$

Solving this system for $\tilde{a}$ and $\tilde{h}$ we obtain

$$\tilde{h} = \sqrt{12A/(P_m^2 - P_L^2)/\tilde{\varepsilon}},\ \tilde{a} = \tilde{h}(1 - \tilde{\varepsilon})/\tilde{\varepsilon}.$$

The minimum mass M_c is determined from Eq. (18) with $\varepsilon_c = \tilde{\varepsilon}$. The optimal parameters of PSC with a tubular structure are found in an analogous manner [3]:

$$\tilde{R} = \sqrt{8A/(P_m^2 - P_L^2)/\tilde{\varepsilon}},\ \tilde{n} = \tilde{\varepsilon}/(\pi\tilde{R}^2).$$

CONCLUSIONS

1. It was shown that under stationary external conditions, when the heat load and the pressure of evacuated vapors are fixed, a necessary and sufficient condition for the sublimation front to remain flat for a porous-sublimation cooling process is that the temperature of the surface being cooled must increase with time.

2. It was proved that the flat shape of the sublimation front in plate-type and tubular PCS can be stable only when the thermal conductivity of the material of the framework of the PSC is not less than a certain value (see Eq. (14)).

3. Relations were obtained for the parameters of PSC for which the temperature of the surface being cooled does not exceed a prescribed value and the sublimation front remains flat throughout the entire cooling process.

4. For plate-type and tubular PSC the parameters for which the flat sublimation front is stable and the temperature of the surface being cooled is minimum or does not exceed a prescribed value with minimum mass of PSC were determined.

NOTATION

q, heat flux density; λ, thermal conductivity; k, permeability; ε, porosity; ε_T, fraction of the volume of pores filled with solid refrigerant; L, thickness of the PSC; ℓ, coordinate of the sublimation front; ρ, density; γ, specific heat of sublimation; μ, molecular weight of the refrigerant; R_g, universal gas constant; η, coefficient of dynamic viscosity; a and h, thickness of the plates and the spacing of the plates for a plate-type PSC; R and h, radius of the capillaries and the number of capillaries per unit area of the surface being cooled for a tubular PSC; M, mass per unit area of the surface being cooled; τ, cooling time, P, pressure; T, temperature; and t, time. The indices are: o, surface being cooled; ℓ, sublimation front; 1, solid refrigerant; 2, vapor; 3, material of the porous framework; L, surface from which vapor is evacuated; c, porous framework; s, state of saturation with the solid and gaseous phases of the refrigerant.

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