ANALYSIS OF THE HEAT AND MASS TRANSFER IN POROUS-SUBLIMATION COOLING

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Conditions are considered for applicability of a model with a moving sublimation front, and factors governing the direction of its motion are clarified. A method is proposed for computation of the temperature of the surface being cooled and the location of the sublimation front as a function of the time for viscous vapor flow. The stability of the plane sublimation front shape is investigated for different cryogenic agents.

Heat from the object that is being cryostatted is removed over a porous skeleton and transmitted to particles of a solid cryogenic agent in the skeleton pores during porous-sublimation cooling (PSC). This results in sublimation of the cryogenic agent and the flow of its vapors in the pores. Since the porous skeleton has a constant thermal contact with the object of the cryostatting, such a cooling method permits getting rid of apparatus pressing the solid cryogenic agent block to the object of the cryostatting [1], which substantially simplifies the construction and raises the reliability of the cryogenic sublimation systems. Processes similar to PSC also proceed in contact sublimation drying (CSD) of food products, medicinal compounds, etc. [2, 3]. However, the heat conduction of such materials is significantly less than of porous metals utilized for PSC [4]. In contrast to CSD, the skeleton heat conduction for PSC is considerably higher than the heat conduction of the phase being sublimated. Moreover, the dependence of the heat conduction on the temperature [3] is ordinarily not taken into account for CSD, which is unacceptable for highly heat conductive PSC materials (copper, aluminum) that have a sharp heat conduction peak in the low temperature domain [5]. The presence of a sublimation front (SF) is assumed in CSD models. Estimates of the width Δl are lacking although the SF concept is meaningless for $\Delta l \gtrsim L$. It is known that the direction of SF front motion depends on the permeability of the material [6, 7], but quantitative criteria governing this direction are not presented. The SF stability domain for CSD is found in [6]. Several stability domains corresponding to different cryogenic agents can exist for PSC.

FORMULATION OF THE PROBLEM

A source of heat liberation creating a heat flux with density q(t) starts to act at a definite time on the surface being cooled of a plane porous block (Fig. 1) containing a solid cryogenic agent. The pressure $P_L(t)$ is given on the cryogenic agent vapor evacuation surface, and the temperature of the surface being cooled $T_0(t)$ must be found.

The quasistationary equations of mass, energy, and momentum balance for a three-component domain consisting of a porous skeleton, solid cryogenic agent, and its vapors are written in the form

$$\frac{\partial G}{\partial x} = \rho_1 \frac{\partial \varepsilon_2}{\partial t}, \tag{1}$$

$$\gamma \frac{\partial G}{\partial x} = \alpha (T_3 - T), \; T = T_1 \approx T_2 \approx T_s(P), \tag{2}$$

$$\frac{\partial P}{\partial x} = -\frac{\eta}{k\rho_2} G, \tag{3}$$

$$\frac{\partial}{\partial x}\left(\lambda_c \frac{\partial T_3}{\partial x}\right) = \alpha (T_3 - T). \tag{4}$$

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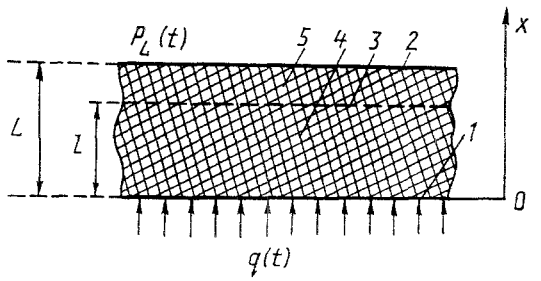

Fig. 1. Diagram of a sublimation cold accumulator with a heat conducting porous skeleton: 1) surface being cooled; 2) evacuation surface of solid cryogenic agent (SC) vapors; 3) SC sublimation surface; 4) three-component domain containing the SC; 5) two-component domain that does not contain SC.

The equations for a two-component domain consisting of the porous skeleton and the cryogenic agent vapors are written analogously (the tilda ~ denotes the two-component domain)

$$\frac{\partial \tilde{G}}{\partial x} = 0, \tag{5}$$

$$\frac{\partial}{\partial x}(\tilde{G}\tilde{h}) = \tilde{\alpha}(\tilde{T}_3 - \tilde{T}), \quad \tilde{T} = \tilde{T}_2, \tag{6}$$

$$\frac{\partial \tilde{P}}{\partial x} = -\frac{\tilde{\eta}}{k_c \tilde{\rho}_2}\tilde{G}, \tag{7}$$

$$\frac{\partial}{\partial x}\left(\lambda_c \frac{\partial \tilde{T}_3}{\partial x}\right) = \tilde{\alpha}(\tilde{T}_3 - \tilde{T}). \tag{8}$$

If there is an interfacial boundary x = l between the two- and three-component domains (this assumption is discussed below), then the boundary conditions for (1)-(8) have the form

$$\lambda_c \frac{\partial T_3}{\partial x}\bigg|_{x=0} = -q(t), \quad G|_{x=0} = 0, \quad \frac{\partial \tilde{T}_3}{\partial x}\bigg|_{x=L} = 0, \quad \tilde{P}|_{x=L} = P_L(t), \tag{9}$$

$$T_3|_{x=l} = \tilde{T}_3|_{x=l}, \quad \frac{\partial T_3}{\partial x}\bigg|_{x=l} = \frac{\partial \tilde{T}_3}{\partial x}\bigg|_{x=l}, \quad T|_{x=l} = \tilde{T}|_{x=l}, \tag{10}$$

$$T|_{x=l} = T_s(P|_{x=l}), \quad P|_{x=l} = \tilde{P}|_{x=l}, \quad G|_{x=l} = \tilde{G}|_{x=l}. \tag{11}$$

The equations of state for the solid cryogenic agent, its vapor, and the porous skeleton are given by the relationships

$$P = P_s(T), \quad \rho_2 = \frac{\mu P_s(T)}{RT}, \quad \eta = \eta_s(T), \quad \gamma \approx \text{const}, \quad \rho_1 \approx \text{const}, \tag{12}$$

$$\tilde{\rho}_2 = \frac{\mu \tilde{P}}{R\tilde{T}}, \quad \tilde{\eta} = \tilde{\eta}(\tilde{T}), \quad \tilde{h} = c_p \tilde{T}, \quad \lambda_c = \varkappa_c \lambda_3(T_3), \quad \varkappa_c = \text{const}, \quad k_c = \text{const}. \tag{13}$$

Using (12) and eliminating G from (2), (3), (9), (11), we obtain

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \alpha(T_3 - T) = 0, \tag{14}$$

$$\frac{\partial T}{\partial x}\bigg|_{x=0} = 0, \quad \tilde{G}|_{x=l} = -\left(\frac{\lambda}{\gamma}\frac{\partial T}{\partial x}\right)\bigg|_{x=l}, \tag{15}$$

where

$$\lambda = kU(T), \quad U(T) = \frac{\gamma \rho_2(T) P_s'(T)}{\eta(T)}. \tag{16}$$

We find from (5), (6), (13)

$$\tilde{G} = \tilde{G}(t) = \tilde{G}|_{x=l}, \quad \tilde{G}c_p \frac{\partial \tilde{T}}{\partial x} = \tilde{\alpha}(\tilde{T}_3 - \tilde{T}). \tag{17}$$

The quantities k, α, $\tilde{\alpha}$ that vary during sublimation are in (14)-(17). There are no theoretical or empirical data governing these quantities. Only rough estimates of k, α, $\tilde{\alpha}$ can be obtained by replacing a real system by a model with a regular porous structure. For instance, we have for a system of circular capillaries and coaxial solid cryogenic agent rods during laminar vapor flow

$$k \sim \frac{\pi n}{12}(r_k - r)^3(r_k + r),\ \alpha \sim \frac{2\pi n\lambda_2}{\ln(r_k/r)},\ \tilde{\alpha} \sim 4\pi n\lambda_2.$$

Even such rough estimates often permit taking simple PSC models in which the quantities k, α, $\tilde{\alpha}$ are not used.

QUALITATIVE ANALYSIS OF THE EQUATIONS

Let us examine a model problem for which we will consider that the quantities α, $\tilde{\alpha}$, λ, λ_c are given constants at a given time. Moreover, we will consider the quantities $\tilde{G}$, $T|_{x=l} = T_l$, l known. In this case we obtain the following system of equations and boundary conditions for T, T_3, $\tilde{T}$, $\tilde{T}_3$ at a given time from (4), (8)-(10), (14), (15), (17)

$$\lambda_c T_3'' - \alpha(T_3 - T) = 0,\ \lambda T'' + \alpha(T_3 - T) = 0,$$
$$\lambda_c \tilde{T}_3'' - \tilde{\alpha}(\tilde{T}_3 - \tilde{T}) = 0,\ \tilde{G}c_p\tilde{T}' - \tilde{\alpha}(\tilde{T}_3 - \tilde{T}) = 0,$$
$$T_3(l) = \tilde{T}_3(l),\ T(l) = T_l,\ \tilde{T}(l) = T_l,\ T_3'(l) = \tilde{T}_3'(l),$$
$$\lambda_c T_3'(0) = -q,\ T'(0) = 0,\ \tilde{T}_3'(L) = 0.$$

The solution of this system has the form

$$T(x) = T_l + \frac{q}{(\lambda_c + \lambda)}\left\{l - x - \frac{1}{\varkappa}[Z(x) - Z(l)]\right\}, \tag{18}$$

$$T_3(x) = T_l + \frac{q}{(\lambda_c + \lambda)}\left\{l - x + \frac{1}{\varkappa}\left[\frac{\lambda}{\lambda_c}Z(x) + Z(l)\right]\right\}, \tag{19}$$

$$\tilde{T}(x) = T_l + \frac{qZ(l)}{\varkappa\lambda_c}\left\{1 - \frac{1}{\varphi(l)}\left[\frac{\alpha}{\varkappa\tilde{G}c_p}\psi(x) + \delta(x)\right]\right\}, \tag{20}$$

$$\tilde{T}_3(x) = T_l + \frac{qZ(l)}{\varkappa\lambda_c}\left\{1 + \frac{1}{\varphi(l)}[\delta(x) - \delta(l)]\right\}, \tag{21}$$

where

$$Z(x) = H(l)\,\mathrm{ch}(\varkappa x) - \exp(\varkappa x), \tag{22}$$

$$H(l) = \frac{[\varphi(l) + \psi(l)]\exp(\varkappa l) + \varphi(l)\lambda_c/\lambda}{\varphi(l)\,\mathrm{sh}(\varkappa l) + \psi(l)\,\mathrm{ch}(\varkappa l)}, \tag{23}$$

$$\psi(x) = \frac{\tilde{\alpha}}{\alpha}\varkappa\{\exp[\beta_2(L - x)] - \exp[-\beta_1(L - x)]\}, \tag{24}$$

$$\varphi(l) = \beta_1\exp[-\beta_1(L - l)] + \beta_2\exp[\beta_2(L - l)]\}, \tag{25}$$

$$\delta(x) = \beta_2\exp[-\beta_1(L - x)] + \beta_1\exp[\beta_2(L - x)], \tag{26}$$

$$\varkappa = \sqrt{\alpha(1/\lambda_c + 1/\lambda)},\ \tilde{\varkappa} = \sqrt{\tilde{\alpha}(1/\lambda_c + 1/\tilde{\lambda})}, \tag{27}$$

$$\tilde{\lambda} = (2\tilde{G}c_p)^2/\tilde{\alpha},\ \beta_1 = \tilde{\varkappa} - \sqrt{\tilde{\alpha}/\tilde{\lambda}},\ \beta_2 = \tilde{\varkappa} + \sqrt{\tilde{\alpha}/\tilde{\lambda}}. \tag{28}$$

We obtain the following expression for the bulk heat flux density Q = $\alpha(T_3 - T)$ between the porous skeleton and the cryogenic agent from (18) and (19):

$$Q(x) = \frac{\alpha q}{\varkappa\lambda_c}Z(x).$$

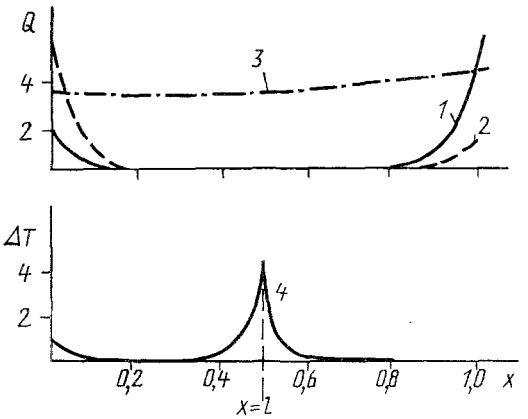

Fig. 2. Bulk heat flux density Q between the porous skeleton and the cryogenic agent and the difference in their temperatures ΔT as a function of the coordinate x for different values of the model problem parameters: 1-3) initial stage of sublimation (l = L); 4) developed sublimation (l < L); 1) $\kappa L = 20$, $\lambda_c = 4$, $\lambda = 1$, L = 1, q = 0.375; 2) $\kappa L = 20$, $\lambda_c = 1$, $\lambda = 4$, L = 1, q = 0.375; 3) $\kappa L = 1$, $\lambda_c = 4$, $\lambda = 1$, L = 1, q = 30; 4) $\kappa L = 20$, $\tilde{\kappa}(L - l) = 20$, $\lambda_c = 10$, $\lambda = 1$, $\tilde{\lambda} = 0.05$, q = 230, L = 1, $l = 0.5$. Q, W/m³; ΔT, K; x, m; λ_c, λ, $\tilde{\lambda}$, W/(m·K); L, ℓ, m; q, W/m².

Investigation of this expression shows that in the presence of sublimation when $l \approx L$, the function Q(x) is quite close to its minimal value min Q in the whole interval (0, L) for $\kappa L \gg 1$. Only near the edges x = 0 and x = L are there narrow boundary layers of width $\Delta l \sim 1/\kappa \ll L$, where Q(x) is noticeably greater than min Q. For $\lambda_c \gg \lambda$ and $\kappa L \gg 1$ we obtain Q(L) ≫ Q(0) (see Fig. 2, curve 1), i.e., the heat transfer between the porous skeleton and cryogenic agent proceeds mainly near x = L. Therefore, a SF occurs here that moves to the surface x = 0 near which a second SF of considerably less intensity appears that should result in the formation of a vapor layer near x = 0. These results are in agreement with experimental CSD data for continuous materials [2, 3]. Since the three-component domain of such materials is almost impermeable (i.e., $\lambda \to 0$), the relation $\lambda_c \gg \lambda$ is also characteristic for them, and SF motion to the surface being heated [2] near which a vapor interlayer is formed [3] is observed for their CSD. For $\lambda_c \ll \lambda$ and $\kappa L \gg 1$ we obtain Q(L) ≪ Q(0) (Fig. 2, curve 2), i.e., sublimation proceeds mainly for the surface being heated and the SF should be removed from it. Precisely such SF motion is observed for the CSD of highly permeable granulated materials with low heat conduction of the porous skeleton [7]. For $\kappa L \sim 1$ the boundary layers in the solution (18)-(28) vanish (Fig. 2, curve 3) while for $\kappa L \ll 1$ we obtain Q(x) ≈ const, i.e., the sublimation is practically homogeneous over the volume of the porous block. Therefore, the model with a SF is valid only for $\kappa L \gg 1$. Let us note that the relationship $\lambda_c \gg \lambda$ is characteristic for PSC since it is desirable to increase λ_c to improve the heat elimination from the object of the cryostatting, and to increase ε_1 to assure maximal cooling time, which results in diminution of λ. If l < L (developed sublimation) and $\kappa l \gg 1$, $\tilde{\kappa}(L - l) \gg 1$, $\lambda_c \gg \lambda$, $\lambda_c \gg \tilde{\lambda}$, $\sqrt{\alpha\lambda} \gg \tilde{G}c_p$, then there follows from (18)-(28) that the differences $\Delta T = T_3 - T$ and $\Delta\tilde{T} = \tilde{T}_3 - \tilde{T}$ decrease exponentially with distance from the boundary x = ℓ (Fig. 2, curve 4) and reach their minimal values at distances $\Delta l \sim 1/\kappa \ll l$, $\Delta\tilde{l} \sim 1/\tilde{\kappa} \ll L - l$ where $Q(l) \gg Q(0)$, $T'_3(l) \ll T'_3(0)$. This means that practically all the delivered heat q goes into sublimation near x = l and the SF moves to the surface being heated. Precisely such a model is used for CSD of continuous materials [2, 3]. It follows from (18)-(28) that for $q/(T_\ell\sqrt{\alpha\lambda}) \ll 1$ we have $\max(\Delta T)/T_l \ll 1$ and $\max(\Delta\tilde{T})/T_l \ll 1$, i.e., the heat transfer between the porous skeleton and the vapor is almost ideal, as is ordinarily assumed in describing CSD [2, 3].

COMPUTATION OF THE TEMPERATURE OF THE SURFACE BEING COOLED

Estimates show that relationships between the parameters are characteristic for PSC for which the model of ideal heat transfer is valid and there is a SF moving to the surface being cooled. In this case $T_3 \approx T$, $\tilde{T}_3 \approx \tilde{T}$, $\lambda_c \gg \lambda$, $T'_3(l) \ll T'_3(0)$ and the following system of equations in $l(t)$, $T_l(l)$, $T(x, t)$ can be obtained from (1), (4), (7), (8), (13)-(15), (17)

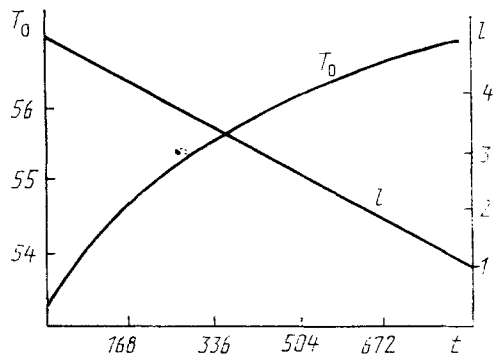

Fig. 3

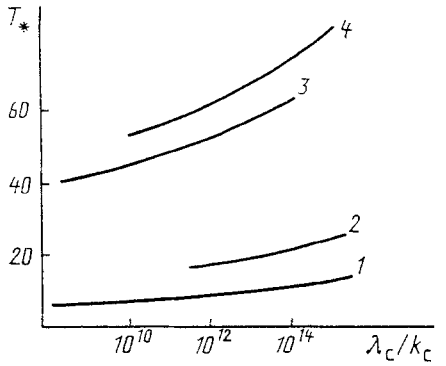

Fig. 4

Fig. 3. Temperature T_0 of the surface being cooled and coordinate l of the sublimation front as a function of the time (example of a computation). T_0, K; l, cm; t, 10^1 sec.

Fig. 4. Maximal temperature T_* of a stable sublimation front for different cryogenic agents as a function of the parameter λ_c/k_c: 1) hydrogen; 2) neon; 3) nitrogen; 4) argon. λ_c/k_c, W/(m³·K); T_*, K.

$$l(t) = l(0) - \frac{1}{\rho_1 \varepsilon_1 \gamma} \int_0^t q(\tau)\, d\tau, \tag{29}$$

$$P_s^2(T_l) = P_L^2(t) + \frac{2R\tilde{\eta}(T_l)\, T_l q(t)\, [L - l(t)]}{\gamma \mu k_c}, \tag{30}$$

$$\frac{\partial T}{\partial x} = -\frac{q(t)}{\lambda_c(T)}, \quad T|_{x=l} = T_l(t). \tag{31}$$

It is taken into account in (31) that, in contrast to CSD, the vapor layer near the surface being heated should not influence the heat elimination from it for PSC since the heat is eliminated mainly over the porous skeleton. The system (29)-(31) was solved numerically by the following method. At each time $t = t_i$ the integral in (29) is calculated by the Simpson method and $l = l(t_i)$ Then (3) is solved by the Brent method and $T_l = T_l(t_i)$ is found. Furthermore, (31) is integrated by the Runge-Kutta method and $T_0(t_i) = T(0, t_i)$ is determined.

The dependences $T_0 = T_0(t)$ and $l = l(t)$ are presented in Fig. 3 as an example of a computation for a sublimation cold accumulator from porous copper containing solid nitrogen. The following initial data were used in this computation: L = 5 cm; $\varepsilon_1 = 0.35$; $k_c = 1 \cdot 10^{-12}$ m²; q = 394 W/m²; $P_s(T) = 6.2 \cdot 10^9 \exp(-827.5/T)$, Pa; $\tilde{\eta}(T) = 6.3 \cdot 10^{-3}\, (T/273)^{1.5}/(T + 104)$, Pa·sec; $\lambda_c = \kappa_c \lambda_3(T_3)$, $\kappa_c = 0.1$; $\lambda_3(T) = 2000\text{-}20\, T$, W/(m·K); $\rho_1 = 960$ W/m³; $\gamma = 243$ kJ/kg.

STABILITY OF THE SUBLIMATION FRONT

The stability conditions for a plane SF shape for CSD have the form [6]:

$$\xi < 1, \quad \text{if} \quad dl/dt < 0; \quad \xi > 1, \quad \text{if} \quad dl/dt > 0,$$

where

$$\xi = \frac{a\gamma P_s'(T_l)}{\lambda_T|_{x \to l-0}}, \quad a = \left| G \Big/ \frac{\partial P}{\partial x} \right|_{x \to l+0}.$$

Taking into account that the relationships

$$\lambda_T|_{x \to l-0} \approx \lambda_T|_{x \to l+0} \approx \lambda_c;$$

$$a = k_c \rho_2(T_l)/\eta(T_l), \quad \text{if} \quad dl/dt < 0; \quad a = k\rho_2(T_l)/\eta(T_l), \quad \text{if} \quad dl/dt > 0,$$

are satisfied for PSC, we obtain the stability conditions in the form

$$\frac{k_c}{\lambda_c} U(T_l) < 1, \quad \text{if} \quad \frac{dl}{dt} < 0; \quad \frac{k}{\lambda_c} U(T_l) > 1, \quad \text{if} \quad \frac{dl}{dt} > 0, \tag{32}$$

where the function U(T) is determined by (16). Taking (16) into account, condition (32) for $dl/dt > 0$ can be written in the form $\lambda/\lambda_c > 1$. But as has been shown above, if $dl/dt > 0$, then $\lambda/\lambda_c \gg 1$, i.e., the SF being removed from the heated surface is always stable. This result is confirmed by experimental data on the CSD of granulated materials [8]. If $dl/dt < 0$, then we obtain the SF stability condition in the form $T_l < T_*$ from (32), where T_* is a root of the equation $U(T_*) = \lambda_c/k_c$. It is taken into account here that the condition $dU/dt > 0$ is satisfied in practice for all cryogenic agents. The dependence of the quantity T_* on the parameter λ_c/k_c is presented in Fig. 4 for the cryogenic agents utilized most often.

CONCLUSIONS

1. Sublimation fronts are formed for porous-sublimation cooling in the case when $\kappa l \gg 1$, where $\kappa = \sqrt{\alpha(1/\lambda_c + 1/\lambda)}$, $\lambda = kU(T)$, $U(T) = \gamma\rho_2(T)P'_s(T)/\eta(T)$. If $\kappa l \ll 1$, then sublimation is practically homogeneous over the bulk of the porous block.

2. Two sublimation fronts moving opposite to each other are formed during cooling. The first front appears near the vapor evacuation surface and the second at the surface being cooled. For $\lambda_c \ll \lambda$ the velocity of first front motion is significantly greater than the velocity of the second, and vice-versa for $\lambda_c \ll \lambda$.

3. If $\lambda_c \ll \lambda$, then the main (second) sublimation front is always stable. For $\lambda_c \gg \lambda$ the stability domain is determined by the front temperature and the ratio λ_c/k_c (see Fig. 4).

4. The relationship $\lambda_c \gg \lambda$ is characteristic for porous-sublimation cooling. A method of computing the temperature of the surface being cooled and the location of the sublimation front as a function of the time has been developed for this case.

5. There is qualitative agreement between the computation model and the experimental data on front stability and motion for contact sublimation drying of continuous and granulated porous materials.

NOTATION

Δl and l are the sublimation front width and its coordinate; L is the porous block thickness; T_0 and q are the heat flux temperature and density on the surface being cooled; T_* is the sublimation front temperature; P_L is the pressure on the vapor evacuation surface; G is the density of the vapor mass flux; T_i, ε_i, ρ_i, and λ_i are the temperature, bulk fraction, density, and heat conduction coefficient of the i-th component; P_s, T_s, η_s are the pressure, temperature, and dynamic viscosity of the saturated vapors of the solid cryogenic agent; α, $W/(m^3 \cdot K)$ and Q, W/m^3 are the bulk heat transfer coefficient and the heat flux density between the porous skeleton and the cryogenic agent; η, h, and c_p are the dynamic viscosity coefficient, the specific enthalpy, and the specific isobaric heat of the vapor; γ is the specific heat of sublimation; λ_T and k are the heat conduction coefficient and permeability of the three-component domain; λ_c and k_c are the heat conduction coefficient and permeability of the porous skeleton; r_k, r are the radii of the capillary and the rod of solid cryogenic agent; n is the density of the number of capillaries, $1/m^2$; R is the universal gas constant; μ is the molecular weight; P is the pressure; x is a coordinate, and t is the time. Subscripts: 1) solid cryogenic agent; 2) vapor; 3) porous skeleton.

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TRANSVERSE TWO-PHASE FLOW AROUND A CYLINDRICAL HEAT EXCHANGE SURFACE

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Particle motion and deposition are modelled numerically on an infinite transversely streamlined cylinder subjected to force factors of a non-turbulent nature.

Considerable attention is expended in the literature on questions of the flow of a gas with particles around bodies. Many of them have been examined in application to problems of impurity filtration, motion of flying vehicles in clouds, and dynamics of atmospheric aerosols [1, 2].

Lately investigations of two-phase flow around obstacles are of great interest for thermal energy problems in connection with the utilization of low-grade solid fuels in boilers and the problems of contamination and erosive wear of convective heat transfer surfaces that occur here. The development of mathematical models of the flow of a gas with particles around heat exchange surfaces is needed to predict the contamination and wear. The approximation of a single particle is the simplest and sufficiently efficient approach when the particle motion is examined in a known field of gas parameters without taking account of the collective effects and reverse influence of the particles. But even in such a formulation two problems will occur, how to describe the motion of the continuous medium and what force factors to take into account in the particle motion equations? Only the aerodynamic drag f_a and gravity f_g forces were taken into account out of the whole set of factors in [3], while the particle motion equations were supplemented in [4] by expressions for the Safmen force f_S, the thermophoresis f_T and the migrational transfer under the action of the fluctuating gas velocity gradient. The viscous boundary layer is taken into account in both papers and the flow outside it is assumed potential. Viscous gas flow with solid particles around an infinite right cylinder was investigated in [5] with the reverse influence of the particles on the gas taken into account. The parameters of the continuous medium were computed in an Euler formulation while only the aerodynamic drag of the medium was taken into account in the Lagrange equations of particle motion.

The common disadvantage of the papers listed is taking incomplete account of the force factors in the particle deposition computations. For instance, there is no Magnus force f_M in the equations of motion in [3-5]. Meanwhile, particle gas suspensions in flows acquire substantial angular velocities (see [6]), consequently, it is impossible to neglect the Magnus force without sufficient foundations. Moreover, the temperature field needed to determine f_T was either not computed generally in these papers [5] or was calculated with the involvement of simplifying hypotheses that do not always have adequate foundations [3, 4].

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