## NOTATION

$u_0$, $u$, $u_F$, $u_E$, initial, current, final, and equilibrium mass contents, g/g solid phase; $a$, mass of adsorbed substance per unit volume of porous body, g/cm³; $\beta = da/dc$, adsorption isotherm parameter; c, mass of vapor in pore space per unit volume of porous body, g/cm³; $D_i$, effective coefficient of internal diffusion, cm²/sec; $R_0$, radius of spherical grain, cm; $D_s$, coefficient of surface diffusion, cm²/sec; S, specific surface, 1/cm; r, pore radius, cm; $\tau$, time, sec; p, adsorbate vapor pressure, g/mole; R, universal gas constant, erg/mole; T, absolute temperature, °K; m, porosity.

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# NONSTATIONARY PROBLEM OF HEAT TRANSFER IN LAMINAR-VACUUM INSULATION


I. S. Zhitomirskii, A. M. Kislov, and V. G. Romanenko



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A mathematical model for nonstationary heat and mass transfer in multilayered insulation for the case of transverse evacuation of the packet is proposed. Results of numerical computations of the gas pressure, the shield temperature, and the heat flux in the packet for certain insulation variants are presented.


Experimental [1-4] and theoretical [4-6] investigations of the heat transfer in laminar-vacuum insulation have shown that one of the fundamental interrelated and simultaneously operating heat-transfer mechanisms therein (radiation, thermal conduction by the gas and by the solid) is thermal conduction by the residual gas. Hence, stationary processes of evacuation of the insulation packet and the heat transfer therein for a steady temperature distribution and molecular gas flow mode are considered in almost all the papers. Theoretical results for the stationary gas pressure distribution in an insulation packet with perforated radiation shields and an estimate of its influence on the heat transfer are obtained for a temperature distribution given in the form of a constant [6] or power-law [4, 7] function of the number of shields. The nonstationary equation of the process of transverse evacuation of the packet was solved


Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR, Khar'kov.


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numerically in [8] for a molecular gas flow; however, the packet was considered isothermal here and the heat transfer through it was not considered.

We propose a mathematical model of the heat-transfer process through an insulation packet with perforated shields in which all three transfer mechanisms are considered interrelated from the time of the beginning of packet evacuation and taking account of internal outgassing. Nonstationary energy and gas flow equations are written for the packet and a method is proposed for their numerical solution. Shield temperature, gas pressure, and heat flux distributions over the packet, as well as their change with time for certain insulation models, are obtained.

A packet of multilayered thermal insulation consisting of N perforated radiation shields separated by washers of porous material and found between the cold (inner) and warm (outer) walls with the temperatures $T_c$ and $T_k = T_k(t)$, respectively, is examined. The warm wall has a system of drainage holes through which the packet cavity communicates with the environment (an evacuated volume) in which the pressure, starting with the time $t > 0$, is a decreasing function of the time $p_k = p_k(t)$. In the initial state [the drainage holes are closed and $p_k(0)$ is on the order of atmospheric pressure], the packet cavity is filled with a single-component and uncondensable gas at the pressure $p_u \geq p_k(0)$. At the time $t = 0$ the drainage holes are opened and transverse evacuation of the primary gas and the gas being liberated by the shield and washer surfaces occurs from the packet cavity.

The mathematical description of the nonstationary heat- and mass-transfer process through the insulation will be carried out for a plane, one-dimensional packet model. Let us number the shields from 1 to N in the direction from the cold to the warm wall. Hence, we agree that the cold wall has the number 0 and the warm, N + 1. The temperature of the n-th shield will be denoted by $T_n = T_n(t)$. Let us assume that the gas flow through the perforated holes (channels) of the shields is quasistationary and that the gas in the n-th gap [between the (n — 1)-th and n-th shields] is in a thermodynamic equilibrium state corresponding to the pressure $p_n = p_n(t)$ in the gap and the mean temperature $T_n' = (T_{n-1} + T_n)/2$, $n = 1, 2, \ldots, N$. We represent the total coefficient of thermal conductivity of the medium in the gap as the sum of conductive and radiative components: $\lambda_n = \lambda^c(T_n', p_n) + \lambda^r(T_{n-1}, T_n)$. Then for the n-th insulation layer (a shield with adjoining half-layers of the washer), the nonstationary energy equation is written as

$$\zeta_n \frac{dT_n}{dt} = \Lambda_{n+1}(T_{n+1} - T_n) - \Lambda_n(T_n - T_{n-1}) - c_p(T_n)\, G_n (T_n - T_{n-1}), \tag{1}$$

where $\Lambda_n = \lambda_n/L \equiv \Lambda(T_{n-1}, T_n, p_n)$. The third term in the right side of the equation takes account of cooling of the layer under ideal heat exchange with the gas.

The conductive and radiative heat transfer between the shields through the porous (fiberglass) washer is determined by formulas from [9], except that a correction taking account of perforation of the shields is introduced for the radiative heat transfer. The perforated shields are considered equivalent to solid shields with the effective absorptivity $\tilde{\varepsilon}$ and radiativity $\tilde{\alpha}$, which depend on $\xi$, $\varepsilon$, and $\bar{l}$. These effective characteristics are determined approximately as follows.

Let black radiation corresponding to the temperatures $T_{n-1}$ and $T_{n+1}$ of adjoining shields be incident on the n-th perforated shield. Then the specific radiant fluxes "absorbed" and "emitted" (including the radiation passing through the perforated channel) by the side of the perforated shield toward the (n — 1)-th shield, for instance, equal

$$\begin{aligned} q_{\text{abs}} &= (1-\xi)\,\varepsilon\sigma T_{n-1}^4 + \xi(w + w_1)\,\sigma T_{n-1}^4, \\ q_{\text{rad}} &= (1-\xi)\,\varepsilon\sigma T_n^4 + \xi(w T_{n+1}^4 + 4\bar{l}\varepsilon w_2 T_n^4)\,\sigma, \end{aligned} \tag{2}$$

where w and $w_1$ are the probabilities of the passage of radiation incident on the channel entrance through the perforated channel and its absorption on the walls; $w_2$ is the probability of the intrinsic radiation of its walls emerging from the channel (for unit flux density). These probabilities are functions of the channel parameters $\varepsilon$ and $\bar{l}$ and their evaluation is a separate problem.

For the sides turned to the (n + 1)-th shield, $T_{n-1}$ and $T_{n+1}$ must change places in (2). Now, if $q_{\text{abs}}$ is divided by $\sigma T_{n-1}^4$ (or $\sigma T_{n+1}^4$ for the second side), and $q_{\text{rad}}$ by $\sigma T_n^4$, and we take

$T_{n+1}^4/T_n^4 \sim 1$, $T_{n-1}^4/T_n^4 \sim 1$, then we obtain the following approximate expressions for the effective radiation characteristics of the shield:

$$\tilde{\varepsilon} = (1-\xi)\,\varepsilon + \xi\,(w + w_1), \quad \tilde{\alpha} = (1-\xi)\,\varepsilon + \xi\,(w + 4\bar{l}\varepsilon w_2). \tag{3}$$

The reduced emissivity $\bar{\varepsilon}$ of the two adjacent perforated shields with the radiation characteristics (3) is evaluated in the usual manner [10] and the formula $\bar{\varepsilon} = \tilde{\alpha}/(2 - \tilde{\varepsilon})$ is obtained.

The coefficient of gas heat-conduction dependent on $T'_n$ and $p_n$ is expressed by the general approximate formula for all flow modes [11]. The thermal conductivity and specific heat of the materials of the insulation packet are determined by empirical relationships [12] for different temperatures.

In analyzing the process of transverse evacuation of the packet cavity, we consider the gas flow through the n-th shield to occur in the nonmolecular (viscous or intermediate) mode if the Knudsen number is $Kn(n) = \bar{L}(T_n, p_n')/D \le \varkappa$, where $p_n' = (p_n + p_{n+1})/2$, and in the molecular mode if $Kn(n) > \varkappa$; $\varkappa \ge 1$. The Knudsen number $Kn(n)$ for the nonmolecular gas flow mode is evidently a nondecreasing function of the number of the shield.

Using the accepted criterion of replacement of the gas flow modes, the shield m which separates the packet into two domains [in one domain the flow through the shield (including the m-th) is nonmolecular, while in the other it is molecular] can be determined. Taking account of this packet separation into two domains, we write the nonstationary gas flow equation for each of the gaps between the insulation shields:

$$V\frac{d}{dt}\left(\frac{p_n}{T_n'}\right) = \frac{g_n}{T_n'} + \begin{cases} F_{n-1}(p_{n-1}-p_n) - F_n(p_n - p_{n+1}), \\ \qquad n = 1, 2, \ldots, m \le N; & (4) \\ F_{n-1}(p_{n-1}-p_n) - A\left(\dfrac{p_n}{\sqrt{T_n'}} - \dfrac{p_{n+1}}{\sqrt{T_{n+1}'}}\right), \\ \qquad n = m+1; & (5) \\ A\left(\dfrac{p_{n-1}}{\sqrt{T_{n-1}'}} - 2\dfrac{p_n}{\sqrt{T_n'}} + \dfrac{p_{n+1}}{\sqrt{T_{n+1}'}}\right), \\ \qquad n = m+2, \ldots, N. & (6) \end{cases}$$

Here $g_n = g(T_n', p_n, t)$ and $F_n = F(G_n)$ are the velocity of outgassing in the n-th gap and the analog of the capacity of the n-th shield in the nonisothermal case, referred to unit surface of the shield; $A = \xi K\sqrt{R/2\pi M}$; $V = \mu L$. Equations (4) and (5) and the expression (6) describe the gas flow in the nonmolecular and molecular modes, respectively. In particular, the flow in the whole packet is nonmolecular for $m = N$ and molecular for $m = 0$. The capacity of the perforated hole is determined for the nonmolecular flow mode of the general approximate formula for all modes [11].

The boundary and initial conditions for (1), (4)-(6) have the form

$$\begin{gathered} T_0 = T_c, \quad T_{N+1} = T_k; \quad T_n(0) = \theta_n, \quad n = 1, 2, \ldots, N; \\ F_0 = 0, \quad p_{N+1} = p_k; \quad p_n(0) = p_u, \quad n = 1, 2, \ldots, N+1. \end{gathered} \tag{7}$$

The initial conditions are given under the assumption that a constant pressure $p_u$ has been maintained for sufficient time in the insulation cavity prior to the evacuation and the temperature distribution over the packet $\theta_n$ has hence been built up. This distribution is the solution of (1) in the stationary case for $p_n = p_u$, $T_0 = T_c$, $T_{N+1} = T_k(0)$.

A numerical method combining factorization over the packet layers with iteration in each time space was used to solve the obtained system of nonlinear differential equations.

Selecting the finite time spacing $\Delta t$ and using the notation $\check{U}_n = U_n(t)$, $U_n = U_n(t + \Delta t)$, where $U_n$ is $T_n$ or $p_n$, we approximate (1), (4)-(6) by a purely implicit difference scheme. To do this, the left sides of the equations are replaced, respectively, by

$$\zeta_n\,(T_n - \check{T}_n)/\Delta t, \quad V\,(p_n/T_n' - \check{p}_n/\check{T}_n')/\Delta t.$$

Consequently, a nonlinear system of algebraic equations in $T_n$ and $p_n$, which is solved by using iteration, is obtained. The iteration process is constructed as follows:

$$\zeta_n^{(s)}\ \frac{T_n^{(s+1)}-\check{T}_n}{\Delta t}=\Lambda_{n+1}^{(s)}\left(T_{n+1}^{(s+1)}-T_n^{(s+1)}\right)-\left(\Lambda_n^{(s)}+c_p^{(s)}G_n^{(s)}\right)\left(T_n^{(s+1)}-T_{n-1}^{(s+1)}\right); \tag{8}$$

$$\frac{V}{\Delta t}\left(\frac{p_n^{(s+1)}}{T_n^{'(s)}}-\frac{\check{p}_n}{\check{T}_n'}\right)=\frac{g_n^{(s)}}{T_n^{'(s)}}+\begin{cases}F_{n-1}^{(s)}\left(p_{n-1}^{(s+1)}-p_n^{(s+1)}\right)-F_n^{(s)}\left(p_n^{(s+1)}-p_{n+1}^{(s+1)}\right), \\ \qquad n=1,\ 2,\ \ldots,\ m; & (9)\\ F_{n-1}^{(s)}\left(p_{n-1}^{(s+1)}-p_n^{(s+1)}\right)- \\ \quad -A\left(\dfrac{p_n^{(s+1)}}{\sqrt{T_n^{'(s)}}}-\dfrac{p_{n+1}^{(s+1)}}{\sqrt{T_n^{'(s)}}}\right), \\ \qquad n=m+1; & (10)\end{cases}$$

$$\frac{V}{\Delta t}\left(\frac{\nu_n^{(s+1)}}{\sqrt{T_n^{'(s)}}}-\frac{\check{\nu}_n}{\sqrt{\check{T}_n'}}\right)=\frac{g_n^{(s)}}{T_n^{'(s)}}+A\left(\nu_{n-1}^{(s+1)}-2\nu_n^{(s+1)}+\nu_{n+1}^{(s+1)}\right),$$

$$\nu_n=p_n/\sqrt{T_n'},\quad n=m+2,\ \ldots,\ N. \tag{11}$$

The system of difference equations (8)-(11) is linear in the quantities $T_n^{(s+1)}$, $p_n^{(s+1)}$, and $\nu_n^{(s+1)}$. The values of $T_n^{(0)}=\check{T}_n$, $p_n^{(0)}=\check{p}_n$, $\nu_n^{(0)}=\check{\nu}_n$ in the preceding time spacing are used as the initial iteration. To solve the system of three-point equations (8), (9)-(11) under the conditions (7) we use a factorization method, where the method of counterfactorization [13] is used for the system (9)-(11). For m = N and m = 0 the counterfactorizations degenerate, respectively, into left and right factorization. The factorization formulas are stable.

Let us note that this same method can be used to find the initial temperature distribution $\theta_n$ over the packet from (1).

To estimate the qualitative regularities of the nonstationary heat- and mass-transfer processes in the insulation under consideration, the transfer equations were solved numerically for certain insulation packet models, and the temperature, gas pressure, and heat flux distributions over the packet were found as a function of the time.

The computations were performed for insulation with perforated aluminum foil shields ($l = 14\cdot10^{-6}$ m, $L = 32\cdot10^{-5}$ m, $\xi = 0.0314$, $\varepsilon = 0.05$, N = 90) and glass-paper SBR-M washers ($\mu = 0.99$, fiber diameter about $6\cdot10^{-6}$ m). The boundary walls had the constant temperatures $T_c = 77$°K and $T_k = 300$°K. Nitrogen was considered as the gas being evacuated (primary and liberated by the packet surfaces).

The initial gas pressure in the packet cavity was assumed to be $1.01\cdot10^5$ Pa (760 torr). The pressure of the environment varied with time according to a piecewise-exponential law in such a way that its value decrease monotonically from $p_k(0) = p_u$ to $p_k = 4\cdot10^{-5}$ Pa ($3\cdot10^{-7}$ torr) in 5 min and then remained constant (Fig. 1a,b).

Two versions of perforated holes distinguished by the relative length $\bar{l} = l/D$ and corresponding to a long ($\bar{l} = 7$) cylindrical channel [14] and a hole in a very thin wall ($\bar{l} = 10^{-2}$) were considered for a constant shield perforation factor. The computation was performed for both versions without inner outgassing in the packet (g = 0) and for outgassing with two constant values of g (in time and over the packet thickness).

The dependences of the gas pressure and specific heat flux at the cold and warm walls of the packet, as well as the stationary temperature distributions over the thickness, obtained as a result of the computations, are presented in Figs. 1 and 2.

From the results obtained the deduction first follows that the buildup time for a stationary value of the heat flux (temperature distribution) in the packet is considerably greater ($10^3$- to $10^4$-fold) than the buildup time for the stationary gas pressure. This difference diminishes with the increase in the rate of outgassing. In turn, this increase is explained by both the rise in gas pressure in the packet and the respective increase in the effective coefficient of thermal conductivity of the insulation. For values of g greater than a certain value [in the computation for $g = 1.33\cdot10^{-4}$ $(m^3\cdot Pa)/(m^2\cdot sec)$], the value of the heat influx to the cold wall during the transition is always higher than the stationary value, which can be of substantial use in estimating the insulation efficiency. It should just be kept

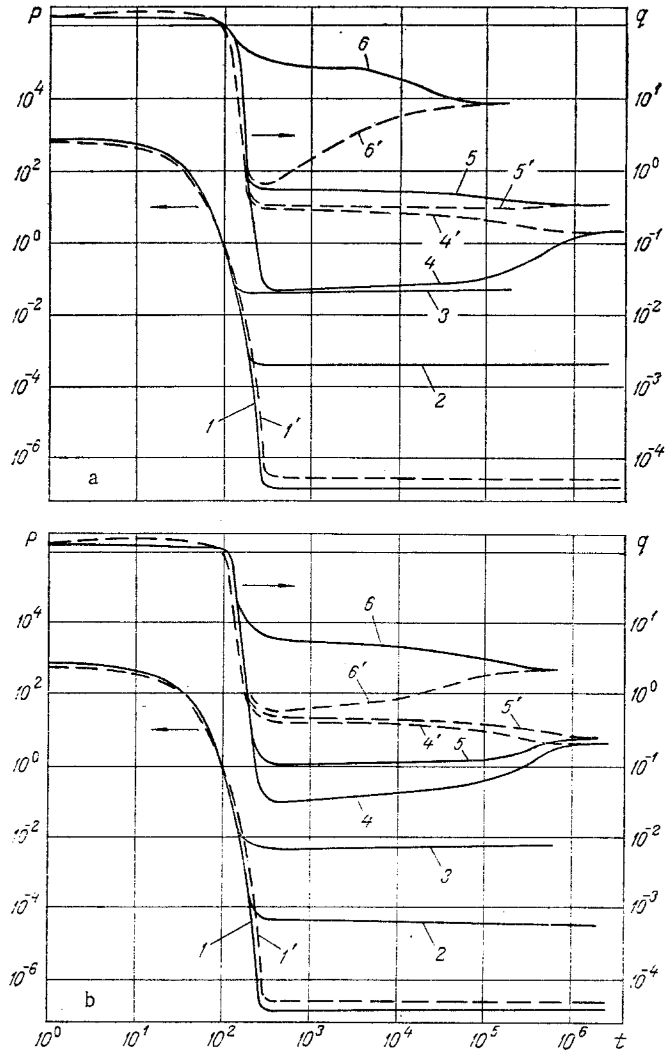


Fig. 1. Gas pressure and heat flux at the cold (solid lines) and warm (dashed line) walls of the packet for $\bar{l}$ = 7 (a) and $\bar{l} = 10^{-2}$ (b): 1,4,4') g = 0; 2,5,5') $1.33 \cdot 10^{-6}$; 3,6,6') $1.33 \cdot 10^{-4}$ (P, 133 Pa; q, $W/m^2$; g, $(cm^3 \cdot Pa)/(m^2 \cdot sec)$; t, sec).

flux to the cold wall during the transition is always higher than the stationary value, which can be of substantial use in estimating the insulation efficiency. It should just be kept in mind that this result has been obtained for the case of a noncondensing gas and a constant rate of outgassing, independent of the time and the temperature distribution over the packet thickness.

The obtained temperature distributions and time dependence of the gas pressure and heat flux in the packet depend on the kind of perforated holes in the shields and the rate of outgassing. Stationary values of the pressure, which vary slightly over the packet and have an abrupt jump only near the warm wall because of the low shield capacity for the perforation factor under consideration, are greater for the case of perforations in the form of channels (type I) than for perforations in the form of holes (type II). This is naturally explained by the lower capacity of the channels. The pressure in the packet also rises with the increase in the outgassing rate (Fig. 1a,b) and hence the nature of the temperature distribution over the packet varies, corresponding to the passage from a heat-transfer mechanism mainly because of radiation to a conductive mechanism because of thermal conduction through the gas (Fig. 2). For the case of the highest value of g, the presence of a pressure jump in the last gap influences the nature of the temperature distribution (a high gradient at the warm wall) exactly as a high temperature gradient holds at the cold wall in the g = 0 case because of the poor heat transfer by radiation for a low shield temperature. Let us note that the curves 2 and 2' for the temperature distribution over the packet (Fig. 2) agree qualitatively with the experimental curves [4, 15].

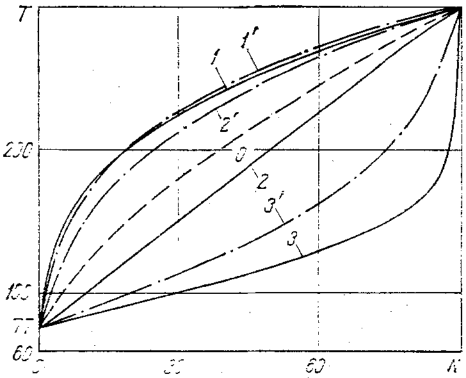

Fig. 2. Steady temperature distribution in a packet: 1,1') g = 0; 2,2') $1.33 \cdot 10^{-6}$; 3,3') $1.33 \cdot 10^{-4}$ ($m^3 \cdot Pa$)/($m^2 \cdot sec$). Dashed curve) $\theta_n$; solid curve) $\bar{l} = 7$; dashed-dot curve) $\bar{l} = 10^{-2}$.

In conformity with the mentioned nature of the change in the stationary value of the pressure and temperature distribution in the packet, the value of the heat influx to the cold wall varies, although the radiant component of the heat transport increases in the case of perforations of type II. The stationary values of the heat influx in the case of perforations of type I (channels) equal 0.158, 0.39, and 8.9 $W/m^2$, and 0.21, 0.24, and 2.46 $W/m^2$ for perforations of type II (holes) for g = 0, $1.33 \cdot 10^{-6}$, and $1.33 \cdot 10^{-4}$ ($m^3 \cdot Pa$)/($m^2 \cdot sec$), respectively (Fig. 1a, b). The effective coefficient of thermal conductivity of the insulation packet, calculated by means of this data, equals $2.3 \cdot 10^{-5}$ ($3 \cdot 10^{-5}$) and $6 \cdot 10^{-5}$ ($3.8 \cdot 10^{-5}$) W/(m·°K) for g = 0 and g = $1.33 \cdot 10^{-6}$ ($m^3 \cdot Pa$)/($m^2 \cdot sec$), respectively, in the case of perforations of type I (II). The experimental values of this coefficient [15] for the same packet with nonperforated shields are $5 \cdot 10^{-5}$–$8 \cdot 10^{-5}$ W/(m·°K).

Therefore, the heat flux for $\xi = 0.0314$ for perforations in the form of holes and $g \neq 0$ turns out to be less than for perforations in the form of channels because of the high capacity of the holes for the gas and, therefore, its lower pressure in the cavity. It can be expected that such a relationship between the heat fluxes (for a fixed g) will be conserved for an increase in $\xi$ up to a certain critical value and will go over into the opposite when the coefficient turns out to be greater than this critical value. Because of the high shield capacity in this case, the absolute value of the gas pressure in the packet will be so low that the heat transfer through the packets will occur mainly by radiation. Then the heat influx through the packet will be greater for shields with perforations in the form of holes than for the case of perforations in the form of channels, since channels transmit radiation more poorly than do holes (or reflect completely [14]).

Indeed, it has been obtained as a result of additional computations for $\xi = 0.2$ and g = $1.33 \cdot 10^{-6}$ $m^3 \cdot Pa/(m^2 \cdot sec)$ that $q \approx 0.41$ (0.72) $W/m^2$ in the case of perforations of the type I (II), i.e., it turns out to be greater for perforations in the form of holes. For comparison, let us mention that under the assumption of total reflection of the radiation by the perforated channels under consideration (diffraction-hole shields [14]), the heat flux is found to equal about 0.167 $W/m^2$.

## NOTATION

N, quantity of shields in the packet; $T_n$, $T_c$, $T_k$, temperature of the n-th shield and cold and warm walls, respectively; $T_n'$, mean temperature in the n-th gap; $p_u$, initial pressure in the packet cavity; $p_k(t)$, pressure of the environment; $p_n$, gas pressure in the n-th gap; t, time; $c_p$, isobaric specific heat of the gas; $G_n$, mass flow rate of the gas through unit surface of the n-th shield per unit time; D, diameter of the perforation hole; $\bar{L}$, mean free path of the gas molecule; K, Clausing coefficient; R, universal gas constant; M, molecular weight of gas; q, specific heat flux; L, spacing between shields; $l$, $\xi$, $\varepsilon$, thickness, perforation factor, and emissivity of the shield, respectively; $\mu$, washer porosity; $\bar{l}$, relative length of the perforation channel; $\zeta_n = \zeta(T_n)$, specific heat of the n-th insulation layer referred to unit shield surface; $\lambda^r$, $\lambda^c$, radiative and conductive coefficients of thermal conductivity; $\lambda_n$, coefficient of thermal conductivity of the medium in the n-th gap; $\theta_n$, initial temperature of the n-th shield.

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# HEAT AND MASS TRANSFER IN LAMINAR-VACUUM INSULATION

R. S. Mikhal'chenko and N. P. Pershin

UDC 536.248.1

Nonstationary heat and mass transfer in laminar-vacuum insulations are investigated experimentally and theoretically in application to their operating conditions in cryogenic vessels.

The heat-transfer process in laminar-vacuum insulation (LVI) is complex in nature and includes heat transfer simultaneously by radiation, by thermal conduction through the LVI material, and by contacts and heat transmission by the residual gas molecules. As has been shown in [1-3], heat transfer through a gas may exert considerable influence on the thermal characteristics of LVI packets. A theoretical investigation of gas flow in LVI for the case of transverse evacuation [4], as well as computations of the thermal LVI characteristics [3] performed by using theoretical dependences for the contact and radiative components of the heat flux and velocity of molecule desorption from the surface of the insulation layers, affords the possibility of representing just the qualitative picture of the heat and mass transfer in LVI, but does not permit quantitative estimates for real insulation systems.

The purpose of this paper is the study of the peculiarities of the insulation evacuation process under conditions of their application in cryogenic vessels and the development of an engineering method of computing the nonstationary heat and mass transfer in LVI by using the experimental results we obtained earlier [5, 6], as well as during execution of this research, on the thermophysical and gasdynamic characteristics of multilayer insulation.

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