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HEAT AND MASS TRANSFER IN LAMINAR-VACUUM INSULATION

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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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Textures which are extensively used at present in heat-shielding systems of cryogenic vessels are selected as insulations to be investigated. Insulation A is a grooved, polyethylene terephthalate (PETP) film, 8 μ thick and aluminized on both sides, with EVTI-7 glass film gaskets. The film has a hole of 2 mm diameter at a 10-mm spacing, the relative perforation area is 0.0314, and the stacking density is 19 shields/cm. Insulation B is soft PETP film, 10 μ thick, with a single-sided aluminum coating and a packing density of 16-19 shields/cm. Insulation was superposed in the form of a wide strip on the side surface of a cylinder with disks on the bottoms during the tests on model cylinder vessels. Insulation B' is the same as B, but the insulated vessel was made by winding a narrow (6 cm) tape.

For a sufficiently large quantity of shields ($N > 10$) the laminar-vacuum insulation can be considered as a homogeneous structure with the thermophysical characteristics λ, a, and c dependent on the temperature and vacuum in the insulation. Then the heat transfer through the insulation is described in the case of a one-dimensional problem by the equation

$$c(T)\rho \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda(T, p)\frac{\partial T}{\partial x}\right]. \tag{1}$$

There are data on the temperature dependence of the coefficient of thermal conductivity and the specific heat as well as on the influence of gas pressure on the LVI thermal conduction for a number of insulations at this time [5, 6]. The gas pressure between the layers is determined by the LVI gas permeability and outgassing, which are functions of the temperature. Hence, in those cases when it is impossible to neglect heat transfer by residual gases, the thermal-conduction equation must be solved jointly with the mass-transfer equation.

We assume in the solution that the multilayer insulation is a homogeneous porous medium which is characterized by outgassing of unit volume W_0 and the specific capacity of unit thickness of the insulation (diffusion coefficient) D. Removal of the gas from the layers during evacuation of the LVI occurs initially in the viscous (and then in the molecular) mode. Because of the relatively short duration of evacuation of the insulation in the viscous mode [4], let us consider only molecular gas flow which sets in at a pressure of 13.3-1.33 Pa [7] for LVI. In the subsequent computations we assume that evacuation of the insulation starts with the pressure 13.3 Pa.

According to the fundamental diffusion law (Fick's law), the gas flow through unit surface is expressed by the relationship

$$q = -D(T)\frac{\partial \rho_g}{\partial x}.$$

Let us write the equation of conservation of the mass of gas flowing through a volume element of insulation $dv = dxdydz$ in the x direction:

$$\frac{\partial \rho_g}{\partial \tau}\,dv = q(x)\,dydz - \left[q(x) + \frac{\partial q(x)}{\partial x}\,dx\right]dydz + W(\tau, T)\,dv,$$

from which we obtain the mass-transfer equation for a one-dimensional stream:

$$\frac{\partial \rho_g}{\partial \tau} = \frac{\partial}{\partial x}\left[D(T)\frac{\partial \rho_g}{\partial x}\right] + W(\tau, T).$$

According to the Clapeyron–Mendeleev equation $\rho_g = p\mu/RT$, the mass-transfer equation is then written in general form as follows:

$$\frac{\partial}{\partial \tau}\left(\frac{p}{T}\right) = \frac{\partial}{\partial x}\left[D(T)\frac{\partial}{\partial x}\left(\frac{p}{T}\right)\right] + \frac{1}{T}W_0(\tau, T). \tag{2}$$

The combined solution of the heat-transfer (1) and mass-transfer (2) equations under appropriate initial and boundary conditions affords the possibility of obtaining the temperature and pressure distributions over the thickness of the insulation at each moment of its evacuation and of finding the magnitude of the heat flux through the insulation.

In order to clarify the nature of the fundamental regularities of the gas flow in the LVI, let us consider the solution of (2) by assuming T = const, D = const, and W_0 = const. Then the mass-transfer equation (2) becomes

$$\frac{\partial p}{\partial \tau} = D \frac{\partial^2 p}{\partial x^2} + W_0. \tag{3}$$

We find the solution of (3) under the following initial and boundary conditions:

$$p(x, 0) = p_{\text{init}}, \tag{4}$$

$$\frac{\partial p(0, \tau)}{\partial x} = 0, \tag{5}$$

$$FD \frac{\partial p(\delta, \tau)}{\partial x} = S[p_1 - p(\delta, \tau)], \tag{6}$$

i.e., it is assumed that the initial pressures over the thickness of the insulation are identical (4), there is no gas stream on the inner layer of the insulation adjoining the vessel surface (5), and the quantity of gas evacuated by the pump equals the quantity of gas which passes through the outer layer of insulation (6). The pressure p_1 is the pressure which assures evacuation of the system in the absence of insulation. We took it to equal $1.33 \cdot 10^{-4}$ Pa in the computations.

In its present form, (3) is analogous to the differential equation of thermal conduction in the presence of heat sources for which solutions have been obtained under the most distinct initial and boundary conditions [8]. Then the solution of (3) in dimensionless form will be the following for the boundary conditions (4)-(6):

$$\frac{p(x, \tau) - p_{\text{init}}}{p_1 - p_{\text{init}}} = 1 + \frac{\text{Po}^*}{2}\left(1 - \frac{x^2}{\delta^2} + \frac{2FD}{S\delta}\right) - \sum_{n=1}^{\infty}\left(1 + \frac{\text{Po}^*}{\mu_n^2}\right) A_n \cos \mu_n \frac{x}{\delta} \exp(-\mu_n^2 \text{Fo}), \tag{7}$$

where $\text{Po}^* = W_0\delta^2/D(p_1 - p_{\text{init}})$ is the dimensionless complex analogous to the Pomerantsev criterion for the solution of the thermal problem, and $\text{Fo} = D\tau/\delta^2$ is the dimensionless time.

In the stationary state (Fo = ∞) the pressure distribution over the thickness of the insulation will be the following:

$$p(x) = p_1 + \frac{W_0(\delta^2 - x^2)}{2D} + \frac{W_0\delta F}{S}. \tag{8}$$

The pressure on the internal insulation layer (x = 0) is

$$p = p_1 + \frac{W_0\delta^2}{2D} + \frac{W_0\delta F}{S}. \tag{9}$$

The results of computing the pressure by means of (7) on the internal layer of the insulation (x = 0) under the assumption S = ∞ are presented in Fig. 1. It was assumed in constructing the graphs that the initial pressure is p_{init} = 13.3 Pa, $p_1 = 1.33 \cdot 10^{-4}$ Pa. The range of variation of $|\text{Po}^*|$ between $1 \cdot 10^{-6}$ and 1 includes the case encountered most frequently in the practice of using LVI.

Analyzing the curves in Fig. 1 and the relationships (7)-(9) obtained, the following general conclusions can be made.

1. The gas pressure in the insulation layers is determined for a given velocity of evacuation by the relationships between the outgassing velocity W_0, the thickness δ of the insulation, and its gas permeability (coefficient of diffusion D). Having results on outgassing and the coefficient of diffusion available, the magnitude of the ultimately achievable vacuum at any point of the insulation can be estimated by means of (8). Attention must be turned to the fact that the pressure in the LVI layers increases in proportion to δ^2. This

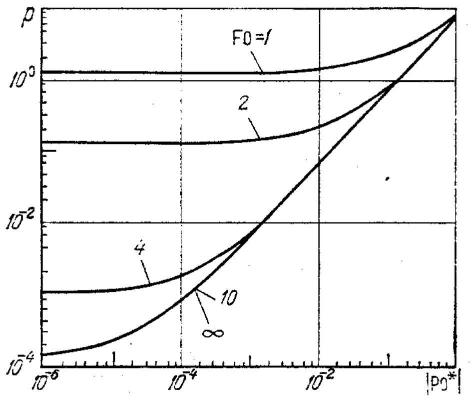

Fig. 1. Dependence of the pressure p (Pa) on the internal layer of the insulation on the numbers |Po*| and Fo for $p_1 = 1.33 \cdot 10^{-4}$ Pa, p_{init} = 13.3 Pa, and S = ∞.

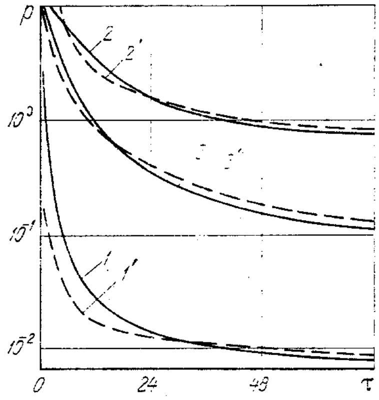

Fig. 2. Pressure p (Pa) on the internal layer of 40-mm-thick insulation as a function of the evacuation time τ, h; 1,1') insulation A; 2,2') insulation B; 3,3') insulation B'; solid line) experimental results; dashed line) computation using (8).

should be taken into account in the practical utilization of the LVI, particularly in selecting the optimal insulation thickness.

2. The pressure distribution over the thickness of the insulation in the steady mode is parabolic.

3. The curves p = f(Po*) merge into one curve in Fig. 1 for Fo = 10 and Fo = ∞. This indicates that the pressure on the internal insulation layer does not vary in practice for Fo > 10. It should be noted that the greater |Po*|, the lower the Fo for which the steady mode sets in, i.e., the greater the outgassing, the more rapidly does the insulation emerge into the equilibrium mode.

4. If evacuation of the insulation is realized at a constant temperature and the outgassing velocity does not change, then the time at which the insulation emerges into the steady mode can be determined from the relationship

$$\tau_{st} = \frac{\mathrm{Fo}_{st}\,\delta^2}{D}. \tag{10}$$

The values of Fo_{st} for which the steady mode sets in are found from Fig. 1. Thus, for a δ = 40 mm thickness in the case of insulation A, for which $W_0 = 6.6 \cdot 10^{-4}$ Pa/sec and $D = 7 \cdot 10^{-5}$ m²/sec, the values are $|Po^*| = 1.1 \cdot 10^{-3}$ and $\mathrm{Fo}_{st} = 10$, as will be shown below. For the unperforated insulation B we have $W_0 = 4 \cdot 10^{-4}$ Pa/sec and $D = 4 \cdot 10^{-7}$ m²/sec, from which $|Po^*| = 1.2 \cdot 10^{-1}$ and $F_{st} = 3$. Then the time to emerge into the steady mode is ~4 min for insulation A and ~3.5 h for insulation B. The time to evacuate the LVI in real vessels is ordinarily several hours. During this time the outgassing velocity does not remain constant, but gradually diminishes. Therefore, the nature of the change in pressure in the LVI will correspond approximately to the nature of the time change in outgassing of the insulation. If the dependence $W_0 = f(\tau)$ and the diffusion coefficient D are known for a definite LVI structure, then the magnitude of the pressure in the insulation layers can be estimated approximately at each instant of its evacuation by means of (8) or the curves in Fig. 1. The accuracy of such a computation will be higher the greater the value of the coefficient D and the lower the rate of change of outgassing in time.

The conclusions presented are verified by the results of an experimental study of the mass-transfer process in LVI at the constant temperature 300°K. The tests were conducted on a cylindrical vessel of 11.5 liters volume which had holes located uniformly over its whole surface. The insulation being investigated was superposed on the vessel. The pressure within the vessel (on the internal layer of the insulation), the vacuum in the chamber, and the flux of gas being evacuated by the pumps were measured during the test. The results obtained on the change in pressure on the internal LVI layer during its evacuation are represented in

TABLE 1. Outgassing Velocity W_0 (Pa/sec) of LVI Textures

Insulation time of LVI	Evacuation in hours					
	1	4	8	16	32	72
A	$1.3\cdot10^{-2}$	$5.3\cdot10^{-3}$	$1.6\cdot10^{-3}$	$1.2\cdot10^{-3}$	$9.3\cdot10^{-4}$	$6.7\cdot10^{-4}$
B	$1.5\cdot10^{-2}$	$7.3\cdot10^{-3}$	$2.3\cdot10^{-3}$	$1.1\cdot10^{-3}$	$6.7\cdot10^{-4}$	$3.0\cdot10^{-4}$
B'	$1.5\cdot10^{-2}$	$6\cdot10^{-3}$	$2\cdot10^{-3}$	$9.3\cdot10^{-4}$	$4.7\cdot10^{-4}$	$1.9\cdot10^{-4}$

Fig. 2 for the initial and boundary conditions (4)-(6). As is seen from Fig. 2, after 3 days of evacuation the pressure on the internal layer of insulation A reaches $6.7\cdot10^{-3}$ Pa. At such a pressure the heat transfer by the residual gases will be negligible compared to the total heat flux through the LVI. The minimal pressure on the internal layer was $6.7\cdot10^{-1}$ Pa for the unperforated insulation B, which is explicitly inadequate for effective operation of the insulation. Insulating the vessel by the tape winding method permitted reducing the magnitude of the pressure in the layers to $1.1\cdot10^{-1}$ Pa, but even at this pressure the heat transfer through the gas can exert a noticeable influence on the total heat transfer through the insulation.

Results of a computation using (8) are presented by the dashed line in Fig. 2 for comparison. The velocity of evacuations S was 30 liters/sec in the tests, the thickness was δ = 40 mm, F = 0.45 m^2. The outgassing velocity of the LVI textures investigated was determined directly during performance of the experiment (Table 1). Values of the specific capacity of the insulation on the vessel (the diffusion coefficient D) were determined experimentally by the method of constant volume during evacuation from the vessel with the insulation superposed of the gas which was liberated from the LVI material during outgassing the vacuum. The diffusion coefficients for the insulations A, B, and B' were $7\cdot10^{-5}$, $4\cdot10^{-7}$, and $1.2\cdot10^{-6}$ m^2/sec, respectively. The experiments to determine the coefficients D were conducted 60 h after evacuation of the vessel with the insulation.

It should be noted that the values of the diffusion coefficients obtained by this same method but with the evacuation of nitrogen or air from the vessel were four- to sixfold higher. This indicates that the initial mass of gas by which the insulation was filled before evacuation should be removed from the interlayer space relatively rapidly. Thus, even for the unperforated insulation B this time is less than 1 h. Henceforth, the magnitude of the vacuum in the layers will be determined by LVI outgassing and the values of the diffusion coefficients relative to the outgassing products which are of complex composition [10].

As is seen from Fig. 2, the computed values of the pressure on the internal insulation layer are close to the experimental values. This indicates that the simple dependences (8) and (9) can be used in a first approximation to estimate the pressure in the LVI layers during its evacuation.

Let us examine the heat and mass transfer in insulation after a vessel has been filled with a cryogenic fluid. As an illustration, let us take the unperforated insulation B for which there are data on the change in the heat flux with the increase in the insulation thickness from 20 to 60 mm [9]. Let us assume that the insulation was first evacuated to a pressure $6.7\cdot10^{-1}$ Pa (Fig. 2), after which liquid nitrogen was poured into the vessel and the further evacuation proceeds from two sides: from the warm wall, because of pumps, and from the cold wall by cryoevacuation. Then the initial and boundary conditions for (1) and (2) can be written as follows:

$$T(x,\ 0)=\text{const},\qquad T(0,\ \tau)=T_1,\qquad T(\delta,\ \tau)=T_2, \tag{11}$$

$$p(x,\ 0)=p_{\text{init}},\quad p(0,\ \tau)=\text{const},\qquad DF\frac{\partial p(\delta,\ \tau)}{\partial x}=S\,[p_1-p(\delta,\ \tau)]. \tag{12}$$

We take data on the temperature dependences $\lambda(T,\ p)$ and $c(T)$ from [5] for an insulation which is similar in its thermal properties to that under consideration (ρ = 23 kg/m^3):

$$c(T)=-0.06+0.65\cdot10^{-2}T-0.136\cdot10^{-4}T^2+1.4\cdot10^{-8}T^3,\ \text{kJ}/(\text{kg}\cdot\text{deg}), \tag{13}$$

$$\lambda(T,\ p) = -0.0345\cdot 10^{-2}T + 0.122\cdot 10^{-4}T^2 + 0.0074\cdot 10^{-6}T^3$$
$$+\alpha\frac{\gamma+1}{\gamma-1}\left(\frac{R}{8\pi}\right)^{\frac{1}{2}}\frac{p}{\sqrt{MT}}\cdot\frac{1}{(\bar{\rho}+1/\delta)},\ \mu\text{W/(cm}\cdot\text{deg).} \tag{14}$$

The diffusion coefficient D at the temperature 300°K for this insulation is $4\cdot 10^{-7}$ m²/sec. Since the diffusion coefficient is determined in the general case by the mean velocity of molecule motion, which is proportional to $\sqrt{T}$, then $D = 2.3\cdot 10^{-8}\sqrt{T}$ m²/sec. The outgassing velocity of the LVI is a function of the temperature. Analyzing the experimental results [10, 11], it can be assumed that the outgassing velocity at a temperature below 300°K will vary according to the law

$$W_0 = \exp\left[-k\left(\frac{1}{T}\right)+b\right]. \tag{15}$$

We determine the values of k and b from available information about the nature of the influence of the temperature on the outgassing velocity [10, 11] and experimental results on outgassing of the insulation B at the temperature 300°K (Table 1). In a first approximation, we assume that the outgassing velocity would take its minimal value $W_0 = 3\cdot 10^{-4}$ Pa/sec after preliminary evacuation and will not later vary in time, but will depend only on the temperature. Then (15) becomes

$$W_0 = \exp\left[-\frac{950}{T} - 4.68\right]. \tag{16}$$

The remaining initial data for the computation are the following: S = 30 liters/sec, $F = 0.45$ m², $T_1 = 77$°K, $T_2 = 300$°K, $p_{init} = 6.7\cdot 10^{-1}$ Pa, $p_1 = 1.33\cdot 10^{-4}$ Pa, $p(0, \tau) = 3.2\cdot 10^{-3}$ Pa according to experimental results obtained for the insulation B on a vessel with holes being cooled to 77°K.

Results of a numerical solution of (1) and (2) for insulation of different thicknesses are presented in Figs. 3 and 4. The mean integrated value of the coefficient of thermal conductivity of the LVI texture investigated is 0.48 W/(cm•deg) for a $1\cdot 10^{-3}$ Pa pressure in the layers in the 300–77°K range. The increase in the coefficient λ_{eff} (Fig. 4) is due to the rise in gas pressure in the layers with an increase in insulation thickness (Fig. 3). As is seen from Fig. 4, the results of computing the coefficient λ_{eff} are close to the experimental data [9], which indicates the validity of the heat- and mass-transfer model used for the LVI. The difference observed in the absolute values and in the nature of the dependence $\lambda_{eff} = f(\delta)$ is explained, on the one hand, by the significant value of the error in the experimental

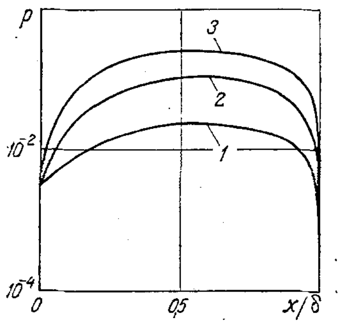

Fig. 3

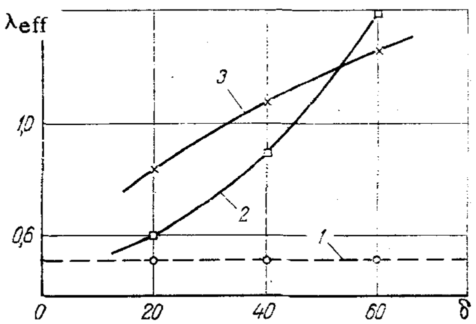

Fig. 4

Fig. 3. Pressure distribution p (Pa) over the insulation thickness: 1) 20 mm thickness; 2) 40; 3) 60.

Fig. 4. Dependence of the effective coefficient of heat conduction [μW/(cm•deg)] of insulation B on the thickness δ (mm) (temperature range 300–77°K): 1) computation using (14) for pressure $1.33\cdot 10^{-4}$ pa in the layers; 2) computation by means of the proposed model; 3) experimental results [9].

determination of the heat flux for different insulation thicknesses. On the other hand, the initial data taken in the computation are not sufficiently exact. This refers primarily to the temperature dependence of the outgassing of the LVI materials. At present, there is practically no information in the literature about how the quantitative and qualitative composition of the gases being liberated from the insulation during its evacuation varies in the 300-100°K range. Also, the question of the influence of the composition of the gases being liberated on the magnitude of the capacity of multilayer insulation requires further refinement.

NOTATION

W, outgassing per unit mass of insulation; W_0, outgassing per unit volume of insulation; D, coefficient of diffusion; x, running coordinate; δ, insulation thickness; q, specific gas flux; p_{init}, initial pressure; F, area of outer layer of insulation; Fo, Fourier criterion; Po^*, Pomerantsev criterion; S, rapidity of evacuation; λ, coefficient of thermal conductivity; c, specific heat; ρ, density of insulation; T, temperature; α, accomodation coefficient; $\gamma = c_p/c_V$, ratio between isobaric and isochoric specific heats; R, universal gas constant; ρ, packing density of the insulation.

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