HEAT TRANSFER IN SEPARABLE CONNECTIONS OF CRYOGENIC SYSTEMS

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Temperature fields were determined theoretically and experimentally for a system of concentric cylinders with gas filling the gap between cylinders under boundary conditions characterized by constant differences in the values of the temperatures at the ends of the connection and by the existence of heat transfer obeying the Fourier law on the cylindrical surfaces of the connection elements.

The important effect of heat flows through insulation on the temperature field of cylindrical bridge connections in cryogenic systems has been pointed out [1, 2]. The purpose of this paper is a study of the qualitative and quantitative effects of heat flows through insulation on the temperature distribution along elements of a separable connection and on the heat flows along it to the cryogenic fluid.

We consider the temperature distribution along a separable connection in the form of two concentric cylinders of length R (Fig. 1) having the temperature T_0 and T_c ($T_0 > T_c$) at the ends. The space between the cylinders is filled by a gas with an effective thermal conductivity λ_g. The outer cylinder and the cold cryogenic piping in the connection section are covered with insulation, the effective thermal conductivities of which have the respective values λ_1 and λ_2.

For a steady-state mode where there is a change in temperature only along the length of the cylinders and no temperature gradient over their thickness as well as constancy of the thermophysical characteristics of cylinder material and insulation, the system of equations for the thermal conductivity of the elements of a separable connection is written in the following manner:

$$\frac{d^2T_1}{dx^2} = \frac{W_g - W_1}{\lambda}, \qquad \frac{d^2T_2}{dx^2} = \frac{W_2 - W_g}{\lambda}. \tag{1}$$

The boundary conditions are

$$T_1(0) = T_0 = \text{const}, \quad T_1(R) = T_c = \text{const}, \qquad T_2(0) = T_0 = \text{const}, \quad T_2(R) = T_c = \text{const}. \tag{2}$$

Heat transfer between the cylindrical surfaces of the elements of the separable connection and the surrounding medium is taken into account in the differential equation as a distributed heat source depending on the coordinates:

$$W_1 = -\frac{\lambda_1}{\delta_1 \cdot \delta}(T_0 - T_1),\ W_g = -\frac{\lambda_g}{\delta_g \cdot \delta}(T_1 - T_2),\ W_2 = -\frac{\lambda_2}{\delta_2 \cdot \delta}(T_2 - T_c). \tag{3}$$

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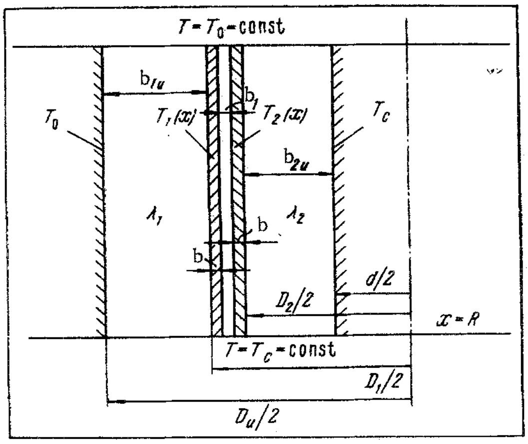

Fig. 1

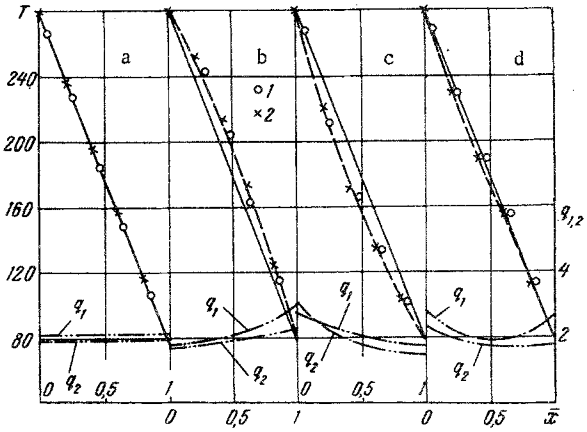

Fig. 2

Fig. 1. Diagram for determination of the temperature field in a separable connection.

Fig. 2. Temperature distribution and thermal fluxes along the elements of a separable connection. Solid curves) T_1 and T_2 from Eqs. (4), $\lambda_1 = \lambda_2 = 1 \cdot 10^{-4}$ W/m · deg; dashed curves) mean value of $T_1(x) - T_2(x)$ from Eqs. (4); a) $\lambda_1 = \lambda_2 = 1 \cdot 10^{-4}$ W/m · deg; b) $\lambda_1 = 1 \cdot 10^{-2}$ W/m · deg, $\lambda_2 = 1 \cdot 10^{-4}$ W/m · deg; c) $\lambda_1 = 1 \cdot 10^{-4}$ W/m · deg, $\lambda_2 = 1 \cdot 10^{-2}$ W/m · deg; d) $\lambda_1 = \lambda_2 = 1 \cdot 10^{-2}$ W/m · deg; dot-dash curves) q_1 and q_2 from Eqs. (7); 1) T_1; 2) T_2 (experiment). T, °K; $q_{1,2}$, W.

The solution of equation system (1) is written in general form as

$$\begin{gathered} T_1 = (k+1-\alpha)(C_1 e^{ax} + C_2 e^{-ax}) + (k+1-\beta)(C_3 e^{bx} + C_4 e^{-bx}) + p(k+1) - kT_c, \\ T_2 = C_1 e^{ax} + C_2 e^{-ax} + C_3 e^{bx} + C_4 e^{-bx} - p, \end{gathered} \tag{4}$$

where

$$\begin{gathered} C_1 = \frac{T_0(k-\beta) + \beta \cdot p - kT_c}{\alpha - \beta} - \frac{[T_0(k-\beta) + \beta \cdot p - kT_c]\, e^{aR} + \beta (T_c - p)}{(\alpha - \beta)(e^{aR} - e^{-aR})}, \\ C_2 = \frac{[T_0(k-\beta) + \beta \cdot p - kT_c]\, e^{aR} + \beta (T_c - p)}{(\alpha - \beta)(e^{aR} - e^{-aR})}, \\ C_3 = \frac{T_0(k-\alpha) + \alpha \cdot p - kT_c}{\beta - \alpha} - \frac{[T_0(k-\alpha) + \alpha \cdot p - kT_c]\, e^{bR} + \alpha (T_c - p)}{(\beta - \alpha)(e^{bR} - e^{-bR})}, \\ C_4 = \frac{[T_0(k-\alpha) + \alpha \cdot p - kT_c]\, e^{bR} + \alpha (T_c - p)}{(\beta - \alpha)(e^{bR} - e^{-bR})} \end{gathered} \tag{5}$$

and

$$\begin{gathered} \alpha = \frac{a^2}{m_g}, \qquad \beta = \frac{b^2}{m_g}, \\ a_1 = m_1 + 2m_g + m_2, \qquad a_2 = m_1 \cdot m_g + m_1 \cdot m_2 + m_2 \cdot m_g, \\ a_3 = (m_1 \cdot m_2 + m_g \cdot m_2)\, T_c + m_1 \cdot m_2 T_0, \\ a = \sqrt{\frac{a_1 + b_1}{2}}, \qquad b = \sqrt{\frac{a_1 - b_1}{2}}, \\ b_1 = \sqrt{a_1 - 4a_2}, \qquad q = \frac{m_g + m_2 - a^2}{m_g}, \qquad h = \frac{m_g + m_2 - b^2}{m_g}, \\ k = \frac{m_2}{m_g}, \qquad p = \frac{a_3}{a_2}. \end{gathered} \tag{6}$$

Equation (4) was analyzed on an M-222 computer. In the general case, the temperature field of the connection is determined by the coefficient of thermal conductivity of the cylinder material, by the thickness of the cylinders, by the effective heat transfer between the warm outer jacket and the outer cylinder, by the heat transfer between cylinders, and by the heat transfer between the inner cylinder and the cryogenic piping.

The equipment for the experimental investigation of temperature distribution along the elements of a separable connection has been discussed [1]. The thermophysical characteristics of the insulation and connection material and the geometric parameters of the connection elements are the following: $T_0 = 282°K$, $T_c = 77°K$, $R = 0.197$ m, $\delta = 1 \cdot 10^{-3}$ m, $\delta_1 = 17.5 \cdot 10^{-3}$ m, $\delta_g = 2 \cdot 10^{-3}$ m, $\delta_2 = 12 \cdot 10^{-3}$ m, $\lambda = 11$ W/m · deg, $\lambda_1 \leq 1 \cdot 10^{-2}$ W/m · deg, $\lambda_g = 0.016$ W/m · deg, $\lambda_2 \leq 1 \cdot 10^{-2}$ W/m · deg.

Calculations made under the assumption of constant cylinder thickness and the experiments showed that for $\lambda_{1,2} < 1 \cdot 10^{-3}$ W/m · deg the variation of the temperature along the elements of a separable connection is given by a linear relation (Fig. 2a); the thermal fluxes along the connection elements, which are given by the expressions

$$q_1 = -\lambda \frac{dT_1(x)}{dx} S_1, \qquad q_2 = -\lambda \frac{dT_2(x)}{dx} S_2, \tag{7}$$

are constant; the presence of gas in the gap has no effect on thermal flow along the connection or on the temperature distribution along it.

With deterioration of vacuum in one of the connection sections, i.e., an increase in the effective coefficient of thermal conductivity of the insulation, $\lambda_1 > 1 \cdot 10^{-3}$ W/m · deg (Fig. 2b) or $\lambda_2 > 1 \cdot 10^{-3}$ W/m · deg (Fig. 2c), a corresponding increase or decrease is observed in the mean integral temperatures of both cylinders in comparison with the previously discussed case.

With deterioration of vacuum in both sections (Fig. 2d), the temperature field at the warm end of the connection is determined by the heat transfer between the inner cylinder and the cold cryogenic piping, and the temperature distribution along the elements is similar to that in Fig. 2c. Thermal fluxes through the insulation of the outer cylinder are a decisive factor for the temperature field of the cold end of the connection (similar to the case shown in Fig. 2b).

The nature of the variation and magnitude of the thermal fluxes along the elements of the connection (Fig. 2b–d) is determined by the quantitative relations of the thermal fluxes to the outer cylinder, the heat transfer along the gas between the cylinders, and the thermal fluxes from the inner cylinder to the cryogenic pipeline.

The calculations and experiments to determine the effect of the thermal conductivity of the gas filling the gap between the cylinders on the temperature field in the connection and the thermal fluxes along it for the case $\lambda_{1,2} > 1 \cdot 10^{-3}$ W/m · deg showed that the temperature difference between the outer and inner cylinders decreased as λ_g increased and the overall thermal losses in the region of the separable connection increased somewhat.

NOTATION

$T_1(x)$, $T_2(x)$	are the temperature of external and internal connection cylinders;
T_0, T_c	are the temperature of warm and cold connection ends;
x	is the current coordinate;
R	is the length of connection;
$\bar{x} = x/R$	is the relative coordinate;
λ	is the thermal conductivity of connection material;
λ_1, λ_2	are the effective thermal conductivity of insulation of external cylinder and cold pipeline at connection section;
λ_g	is the effective thermal conductivity of gas in the gap between cylinders;
δ_{1u}, δ_g, δ_{2u}	are the thickness of insulation for external cylinder, gap between cylinders, and cold pipeline at connection section;
δ	is the thickness of connection cylinder;
S_1, S_2	are the cross-sectional areas of external and internal connection cylinders;
$\delta_1 = \delta_{1u}\sqrt{D_1/D_u}$	is the effective thickness of external cylinder insulation;
$\delta_2 = \delta_{2u}\sqrt{D_2/d}$	is the effective thickness of internal tube insulation within connection section;
D_1, D_2, d, D_u	are the diameters of external cylinder, internal cylinder, cryogenic pipeline, and envelope.

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