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HEAT EXCHANGE IN CRYOSTAT THROATS WITH COAXIAL EXTENSION ELEMENTS

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The heat exchange in cryostat throats with coaxial extension elements is investigated theoretically and experimentally. It is shown that the efficiency of the coaxial element falls sharply when its length is increased.

In helium cryostats with wide throats intended for cooling relatively large objects, the main part of the heat influx to the liquid helium is heat from the walls of the throat and along the gas colume inside it. The heat influx, and, consequently, the loss of helium by evaporation, can be reduced by increasing the thermal resistance of the walls of the throat. For large-diameter cryostats it was suggested in [1] that throats made in the form of coaxial cylinders should be used. It was experimentally established [1] that forced cooling of both walls of the coaxial element using a cylindrical baffle (Fig. 1, 9) lowered into its end gap and hermetically attached to the thermal lid of the cryostat, does not lead to a reduction in the heat influx.

The temperature profile, taking into account the heat exchange by the gas in the gap between the two walls (Fig. 1, I), can be described by the following two equations:

$$\frac{d^2t_1}{dx^2} - \mu^2 |t_1 - t_2| = 0, \tag{1}$$

$$\frac{d^2t_2}{dx^2} + \mu^2 |t_1 - t_2| = 0. \tag{2}$$

Since the temperature profiles of both walls of the coaxial element are symmetrical $|t_1 = -t_2|$, the system of equations can be reduced to the single equation

$$\frac{d^2t_1}{dx^2} - 2\mu^2 t_1 = 0. \tag{3}$$

For the boundary conditions

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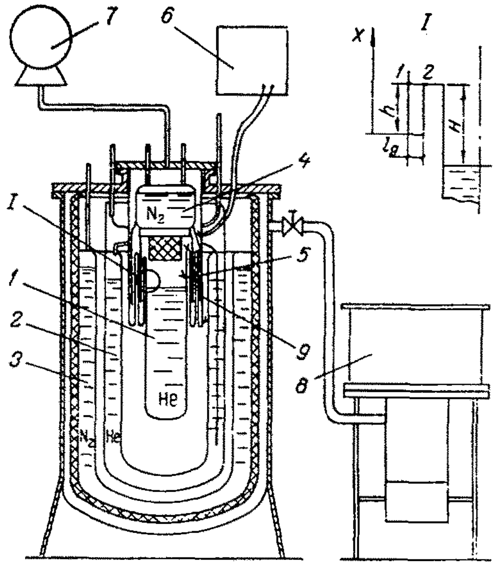

Fig. 1. Arrangement for investigating the heat influx along throats: 1) experimental vessel with coaxial throat; 2) helium protective chamber; 3) nitrogen protective chamber; 4) nitrogen bath; 5) manganin–constantan thermocouple; 6) R-306 potentiometer; 7) GSB-400 gas meter; 8) vacuum apparatus; 9) baffle.

$$x = 0,\ t_1 = 0;\ x = h,\ t_1 = 1$$

the solution of (3) has the form ($\mu \neq 0$)

$$t_1 = \frac{\operatorname{sh}\mu\sqrt{2}\,x}{\operatorname{sh}\mu\sqrt{2}\,h}, \qquad \frac{dt_1}{dx} = \frac{\mu\sqrt{2}\operatorname{ch}\mu\sqrt{2}\,x}{\operatorname{sh}\mu\sqrt{2}\,h}. \tag{4}$$

The specific thermal resistance of the coaxial element is given by

$$R = \frac{\Delta t}{\lambda_w \left(\dfrac{dt}{dx}\right)_{x=h}} = \frac{\Delta t}{\lambda_w \mu\sqrt{2}\operatorname{cth}\mu\sqrt{2}\,h}. \tag{5}$$

The specific thermal resistance of the walls of the same height $R_0 = h\Delta t/\lambda_w$.

The ratio of the thermal resistances of the element considered when there is heat exchange through a gas layer and without heat exchange is equal to

$$\eta = \frac{R}{R_0} = \frac{1}{h\mu\sqrt{2}\operatorname{cth}\mu\sqrt{2}\,h}. \tag{6}$$

In helium cryostats the walls of the throat are cooled by evaporation of the helium. In this case both free and forced convection may be observed in the gap of the coaxial element.

To check the applicability of the theoretical relations obtained to cryostat throats we carried out experimental investigations using a model of a vertical cylindrical vessel with coaxial elements. The first model (Fig. 1) of the throat consisted of four coaxial cylinders with a wall thickness of 0.8 mm. The height of the coaxial structure was 430 mm and the gap was 8.5 mm. To reduce the heat influx from the cover a nitrogen bath was placed in the first part of the vessel. The second model of the throat consisted of two coaxial cylinders 0.8 mm thick. The height of the coaxial part was 200 mm and the gap was 9 mm. In order to eliminate heat influx from the cover a hollow plastic plug 200 mm high with polished copper screens on the cold and hot ends was inserted into the first part of the throat.

The diameter of the inner cylinder of both models was 200 mm and the height was 700 mm.

As an example, we calculated the efficiency of the inner loop of the throat of model 1 having the following parameters: $l_g = 85 \cdot 10^{-3}$ m, $l_w = 0.8 \cdot 10^{-3}$ m, and h = 0.43 m.

The product of the Grashof and Prandtl numbers was less than 10^3, and consequently $\lambda_{eq} = \lambda_g$.

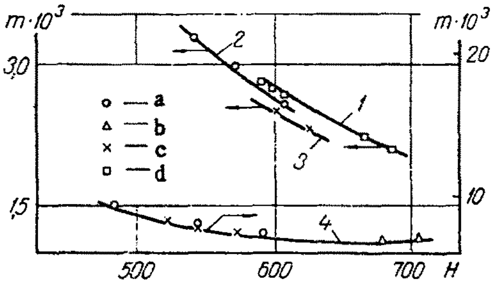

Fig. 2

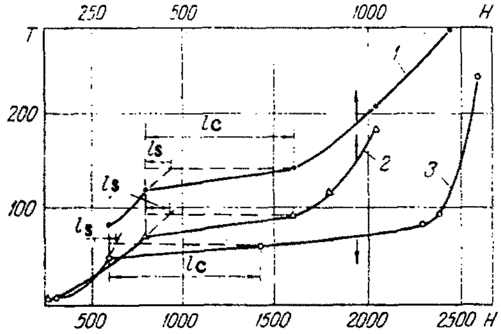

Fig. 3

Fig. 2. Curves of the evaporability as a function of the height of the throat on models ($m \cdot 10^3$, g/sec; H, mm): a) with a copper baffle; b) with a baffle of Kh18N10T steel; c) without the copper baffle; d) with shortened loops; 1-3) experiments on helium on model 1; 4) experiments on nitrogen on model 2.

Fig. 3. Experimental curves of the temperature distribution along the height of the throat with a coaxial element expanded along its length (T, °K; H, mm): 1) model 2 (experiment on nitrogen); 2) model 2 (experiment on helium); 3) model 1 (experiment on helium).

We thus have

$$\mu = \sqrt{\lambda_{eq}/\lambda_w l_g l_w} = \sqrt{0.044/5.5 \cdot 0.8 \cdot 10^{-3} \cdot 8.5 \cdot 10^{-3}} = 34.2\ \mathrm{m}^{-1}.$$

The values of λ_g and λ_w were taken for the arithmetic mean temperature of the walls of the coaxial loop. For this value of μ we obtain the following value of the efficiency of the coaxial loop:

$$\eta = \frac{1}{\mu\sqrt{2}\,h\,\mathrm{cth}\,\mu\sqrt{2}\,h} = \frac{1}{34.2 \cdot \sqrt{2} \cdot 0.43 \cdot 1} = 0.049.$$

The height of the straight part of the throat, equivalent to the coaxial loop, $L_{eff} = h\eta = 0.430 \cdot 0.049 = 20.7 \cdot 10^{-3}$ m.

The vertical cylindrical vessel 1 (Fig. 1), the lower part of which is filled with liquid helium, is surrounded by a protective helium chamber 2 and a protective nitrogen chamber 3.

The method for determining the heat influx to the cryogenic liquid is based on a measurement of the flow rate of evaporated liquid using a GSB-400 gas meter. We measured the temperature along the walls of the throat using a manganin–constantan thermocouple and an R-306 potentiometer.

Tests of model 1 were made with throats placed in the loop to direct the flow of gas, and without them. In addition, the model was tested with "shortened" coaxial loops. To do this a copper ring 20 mm high was pressed into the upper part of the loop.

In Fig. 2 is shown the experimental data with respect to the rate of evaporation of liquid helium for different values of H (Fig. 1) for all variants of model 1. The experimental effectiveness of the coaxial loops was determined with respect to the relationship between the evaporation rate with shortened loops and with loops without a baffle.

For example, for a throat height H of 620 mm this ratio was 1.12. As was shown above, the value of L_{eff} of one loop of this model is 21 mm. For the second loop calculation gives L_{eff} = 35 mm. The theoretical value of the ratio of the thermal resistances is (620 + 21 + 35)/620 = 1.091, which is in satisfactory agreement with experiment.

The efficiency of the coaxial element in model 1 was found in addition by measuring the temperature profile of the metal wall as follows. Figure 3 shows experimental curves of the temperature distribution along the height of the throat with a coaxial element expanded along its length. The thermal resistance of any part of the throat is proportional to the temperature drop along this part when the heat flux along the wall is constant. When the coaxial element is replaced by a straight section, giving the same thermal resistance of the throat,

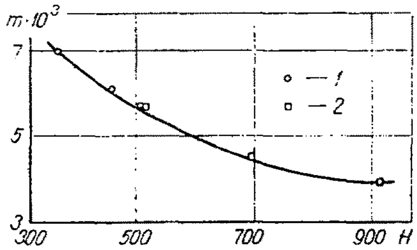

Fig. 4. Rate of evaporation of helium as a function of the height of the throat in cryostats with different heights of coaxial loop ($m \cdot 10^3$, g/sec; H, mm): 1) 150 mm; 2) 300 mm.

the curve of the temperature distribution along this section is represented by a dashed line equidistant from the experimental curve over the same temperature range. The efficiency of the coaxial element is defined as the ratio of the length of the replacing straight part l_s to the expanded length of the coaxial element l_c. The experimental values of the efficiency obtained in this way were 0.049 for the "inner" loop, and 0.052 for the outer loop, which agrees satisfactorily with calculations.

The efficiency of the coaxial element in model 2 was found solely by temperature measurements (Fig. 3) and by calculation. The experimental value of the efficiency, equal to 0.11 in the experiment on helium and 0.27 in nitrogen, agrees well with calculations. The insertion of the copper baffle to produce forced convection in the gap did not reduce the heat influx. In model 2, in the experiment on nitrogen, the heat flux did not change when the copper baffle was replaced by a baffle made of Kh18N10T steel 0.5 mm thick.

To check the theoretical relations we made tests on two helium cryostats of 300-mm diameter and wall thickness 0.6 mm, which had different heights of the coaxial loop, viz., 150 mm and 300 mm. The results of the tests are shown in Fig. 4.

An increase in the height of the coaxial loop by a factor of 2 did not reduce the heat influx to the liquid helium.

Hence, it follows from the results obtained that it is not worthwhile to use a coaxial throat in cryostats of similar geometrical dimensions. An increase in the length of the loop by greater than a certain amount gives practically no increase in its thermal resistance. Cryostats with a coaxial loop in the throat are fairly complex in construction and are difficult to make. Calculations show that a coaxial loop can be effective in cryostats of comparatively small dimensions in which the thermal resistance of the wall of the throat is less than the thermal resistance of the gas layer.

NOTATION

t_1 and t_2, relative temperature of walls 1 and 2; $t = (T - T_0)/T_0$; T_0, temperature of the wall at $x = 0$; $\mu^2 = \lambda_{eq}/\lambda_w l_w l_g$; l_g, width of the gas layer; l_w, wall thickness; λ_w, thermal conductivity of the material of the wall; λ_{eq}, equivalent thermal conductivity of the gas, taking into account free convection in the gap [2]; R, specific thermal resistance of the wall; η, efficiency of the coaxial loop; h, height of the coaxial loop; and H, height of the throat.

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IMPREGNATION OF A HEATED FILLER WITH A VISCOUS LIQUID

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The kinetics of the penetration of a viscous liquid (connecting) inside a preliminarily heated porous body (the filler) moving inside it is considered.

When manufacturing many composite materials employed in technology the process of impregnating a certain porous body, which plays the further role of a filler of the composite material, with a viscous liquid is widely employed. The viscous liquid later changes into a solid due to crystallization or vitrification on cooling, polymerization, etc. and plays the part of a solid binding matrix. The viscosity of the liquid, even at high temperatures, is often too high, and the filler is too dense so that the hydraulic resistance experienced by the liquid when filtering through the filler is also high, and when impregnating it is necessary to apply extremely high pressure gradients which cannot easily be employed under practical conditions. Prolonged heating of the liquid to comparatively high temperatures to reduce its viscosity is undesirable in view of possible thermal expansion of the liquid or acceleration of other physicochemical processes occurring in it, and reactions which would reduce the quality of the composite material obtained. Such a situation usually arises when making many thermoplastics, glass-plastic materials, and a number of other composite materials.

One of the methods of eliminating these difficulties is by preliminary heating to high temperatures of the filler itself for relatively moderate preliminary heating of the liquid. This enables one to confine the duration of the intense heating of the liquid within permissible limits, which considerably facilitates its penetration into the filler. Hence, it is necessary to consider heat conduction in the filler–liquid system and filtering of the liquid simultaneously, taking into account the nonlinear dependence of its viscosity on the temperature.

The specific system considered is shown in Fig. 1. It represents a realistic model of certain systems used in practice for producing composite materials. In the region of negative x the filler is heated in a gaseous medium under a pressure p' (often reduced compared with atmospheric pressure) to a temperature T', which may sometimes reach thousands or more degrees Centrigrade. Hence, in region I of the filler, which may be a bunch of parallel fibers, a system of interlaced fibers, cloth material, etc., its pores are filled with gas under the pressure p'. The filler is drawn with constant velocity u into the chamber II, filled with liquid at a temperature $T'' < T'$ and a pressure $p'' > p'$. Under the action of the pressure drop which occurs, the liquid, heated by heat transfer with the filler, penetrates deeper into it, displacing gas, and at distances $x \geq L_x$ from the entry to the chamber II completely fills its pores. Thus, in addition to region I inside the filler there is a region III with pores filled with liquid; the boundary of the region is described by a certain function $Y(x)$. The length of the working part of the apparatus L_x (where $Y(L_x) = L_y$), its dependence on the various parameters of the process and the physical characteristics of the filler and liquid, and also possible methods of reducing this length while simultaneously increasing the rate of spread u, which helps to intensify the process, are of particular practical interest.

In this paper we will only investigate the plane problem (a "strip" of filler is drawn, the transverse dimensions of which in the direction perpendicular to the plane of the figure is far greater than L_y), and we will assume that the penetrability of the filler, the density and specific heat of the material of the filler and liquid and also the effective thermal conductivities are independent of the pressure and temperature.

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