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TIME TO COOL A CRYOGENIC OBJECT BY A GASEOUS CRYOGENIC AGENT

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Dependences to compute the cooling time of a single-channel object are obtained theoretically and confirmed experimentally.

The heat-transfer—flow-through part of modern cryogenic apparatus is a system of channels with $L/d > 1000$ as a rule. Cooling such apparatus, i.e., reducing the temperature from the initial to the working value, is performed by a single-phase cryogenic agent. The cooling time here can reach several days. The purpose of the present paper is to determine the cooling time and to estimate the parameters influencing its value most strongly.

The problem can be formulated as follows: A cryogenic agent whose temperature does not vary during the cooling process goes into a channel with a constant initial temperature. Determine after what time the end of the channel takes on the temperature of the cryogenic agent.

The solution applied to a steam-generating channel, obtained in [1, 2], can be used to find the cooling time. The dynamic process is described in [1, 2] by two energy equations

$$\frac{Dc_p}{\alpha F_s}\frac{\partial T}{\partial \tau}+\frac{Gc_p}{\alpha U}\frac{\partial T}{\partial z}=\Theta-T,$$
$$-\frac{Mc_m}{\alpha F_s}\frac{\partial \Theta}{\partial \tau}=\Theta-T \qquad (1)$$

with the boundary conditions

$$\Theta(z,\ 0)=T(z,\ 0)=T_0,\ T(0,\ \tau)=T_{in}=\text{const}.$$

By introducing the new independent variables

$$\zeta=\frac{z\alpha F_s}{LGc_p},\quad \eta=\frac{\tau-z/W}{Mc_m}\alpha F_s \qquad (2)$$

we obtain the solution of system (1) in the form of infinite series in ζ and η. A singularity of this solution is the determination of the finite value of the time for any point of the channel to reach the working temperature. The complex form of the solution forced the authors of [1, 2] to tabulate the dimensionless temperature T/T_{in} for a broad range of values

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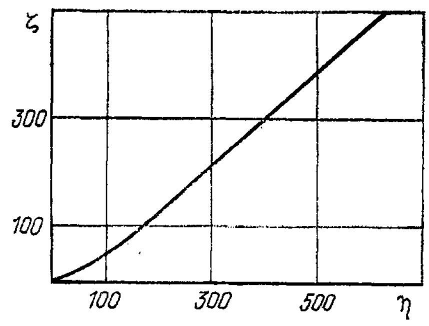

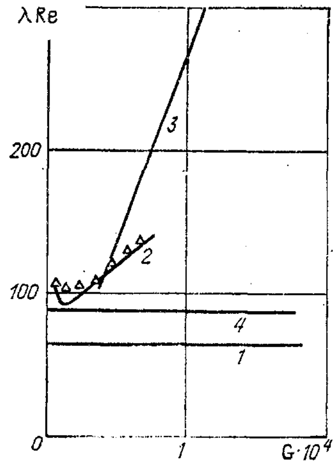

Fig. 1 Fig. 2

Fig. 1. Dimensionless cooling time according to [1, 2].

Fig. 2. Dependence $\lambda Re = \lambda Re(G)$: 1) straight channel; 2) cambered channel ($d = 2.6$ mm, $\phi = 140$ mm); 3) corrugated channel ($d = 6$ mm); 4) coaxial channels with three longitudinal positioners ($d = 4$ mm, $\phi = 5$ mm); the points are experimental data on exhausting a test element. $G \cdot 10^4$, kg/sec.

of ζ and η. However, the use of such tables is associated with known inconveniences. In subsequent papers, in [3], say, an attempt was made to find acceptable engineering solutions of the temperature profile approximations at any channel section and at any time:

$$\frac{T - T_{in}}{T_0 - T_{in}} = \exp\left(1 - \frac{\eta}{\zeta}\right). \tag{3}$$

This dependence describes the main part of the temperature profile.

In conformity with (3), compliance with the condition $T = T_{in}$ denotes termination of the cooling process. The cooling time η hence tends to infinity. This latter means that the proposed equation cannot be used to determine the total cooling time. Another method to simplify the solution obtained in [1, 2] is to use the so-called "temperature jump" model that assumes that the total heat-transfer zone is very much less than the channel length. In this case, the thermal balance method can be used to determine the cooling time.

In this paper, an approximation is proposed for the "exact" analytic solution that permits determination of the total cooling time for an object with the heat transfer between the gas and the channel wall taken into account. To do this we turn to system (1) whose solution is obtained, as has been noted earlier, in the complex analytical form:

$$V = \frac{T_0 - T}{T_0 - T_{in}} = f(\zeta, \eta). \tag{4}$$

Since the running temperature of the cryogenic agent equals the input temperature at the end of the process, then on this basis the relation between the two independent variables can be found

$$f(\zeta, \eta) = 1. \tag{5}$$

The results of computing the dependence (5) are represented in Fig. 1. Seen clearly in the figure is the linear dependence of the dimensionless channel length on the cooling time for $\zeta \geq 100$ and a power-law dependence for $\zeta \leq 100$. This permits approximating this graph by the corresponding equations:

$$\tau = 7 \frac{Mc_m}{(\alpha F)^{0.3} (Gc_p)^{0.7}} \quad \text{for} \quad \zeta \leqslant 100, \tag{6}$$

$$\tau = 1.17 \frac{Mc_m}{Gc_p} + 52.5 \frac{Mc_m}{\alpha F_s} \quad \text{for} \quad \zeta \geqslant 100. \tag{7}$$

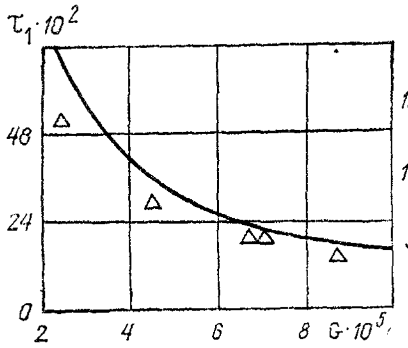

Fig. 3

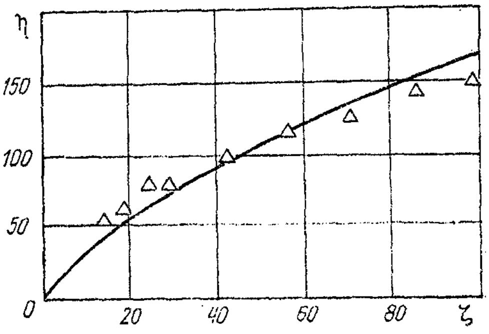

Fig. 4

Fig. 3. Experimental points and theoretical curve of cooling time values for a test element (first period). $\tau_1 \cdot 10^2$, sec.

Fig. 4. Comparison of the computed (curve) and experimental (points) data to determine the dimensionless cooling time.

The accuracy of a computation using (6) and (7) as compared to (5) is 3.5 and 0.5%, respectively. Therefore, simple computational dependences have been obtained to determine the cooling time of a single channel of length ζ by a constant flow rate of cryogenic agent. On the basis of comparing the length of the heat-transfer zone with the channel length, channels of length $\zeta \leq 10$ can be considered "short" channels, $10 < \zeta < 80$ "medium," and $\zeta \geq 80$ "long."

The diminution of ζ, and therefore of the cooling time as well, can be realized by increasing the flow rate of cryogenic agent, as is seen from (2), and this is performed in a natural manner under the condition of maintaining a constant pressure at the channel input.

The problem of cooling a single channel under the condition $P_{in} = \text{const}$ was considered in [4, 5]. The method of the "temperature jump" was used in both papers, where a straight smooth channel was considered in [4], and a coaxial channel in [5] in which the main resistance is the resistance of the electrical insulator positioners. As is seen from the above, neither paper substantially takes account of the second cooling period when the influence of the flow rate is diminished and the final value of the heat-elimination coefficient becomes the governing factor in determining the cooling time. For the opportunity to take account of the heat-elimination coefficient, we turn to the mode $G = \text{const}$ examined above. The cooling time for this case, determined by the model of a "temperature jump," is

$$\tau = \frac{Mc_m}{Gc_p}, \tag{8}$$

which can be represented in the form

$$\frac{\tau\alpha F_s}{Mc_m} = \frac{\alpha F_s}{Gc_p} \tag{9}$$

or, if the thermal accumulation of the cryogenic agent flux is neglected,

$$\eta = \zeta. \tag{10}$$

It can be shown that upon complying with condition (10) corresponding to the "temperature jump" model, the value of the dimensionless temperature is $V_1 = 0.5$. On this basis, the whole channel cooling process can provisionally be separated into two periods: 1) the time of variation of the dimensionless temperature V_1 at the channel end is 0-0.5 and 2) 0.5-1. If we go over to the initial variables in (6) and (7), it then becomes clear that the first cooling period which depends only on the flow rate is governing for "long" channels, while both periods will depend on the flow rate and intensity of the heat transfer for the "short" and "medium" channels and can be commensurate. Indeed, if the concept of the relative magnitude of the second cooling period is introduced, then this magnitude, equal to $\tau_2/(\tau_1 + \tau_2) = 1 - 0.14\zeta^{0.3}$, for the "short" and "medium" channels, can vary between 40 and 100%, and for

$$\frac{\tau_2}{\tau_1 + \tau_2} = 1 - \frac{1}{1.17 + 52.5/\zeta}$$

can vary from 15-40% for "long" channels. It follows from the above that a condition for applicability of the "temperature jump" model can be obtained in the form $\alpha F/Gc_p \gg 40$. Therefore, by returning to the mode P_{in} = const, we can expect that even in this case the first cooling period should be found by the model of a "temperature jump." The determination of the second period, due to the heat-elimination coefficient, is made complicated by the necessity for a combined solution of the equation of motion which is a result of the variable flow rate and the two energy equations. These difficulties can be avoided if the cooling mode with variable flow rate of the cryogenic agent is replaced in such a way that the cooling times ofboth modes, determined by the "temperature jump" model, would be equal. On this basis, the first cooling period equals

$$\frac{Mc_m}{G_{equ}c_p} = \frac{Mc_m}{c_p}\int_0^1 \frac{d\bar{z}}{G(\bar{z})}, \tag{11}$$

from which

$$G_{equ} = 1 \Bigg/ \int_0^1 \frac{d\bar{z}}{G(\bar{z})}. \tag{12}$$

The passage to the cooling mode of constant flow rate of cryogenic agent that has been performed permits determination of the total time of the two periods:

$$\tau = 1.17\,\frac{Mc_m}{c_p}\int_0^1 \frac{d\bar{z}}{G(\bar{z})} + 52.5\,\frac{Mc_m}{\alpha F_s}. \tag{13}$$

The $G(\bar{z})$ in (12) and (13) is the cryogenic agent flow rate as a function of the location of the cooling front. If the value of the complex λRe depends linearly on the flow rate (Fig. 2), i.e., $\lambda \mathrm{Re} = AG + B$, then it can be shown that the formula to determine the flow rate of the cryogenic agent will have the form

$$G = m + \left(\frac{f + g\bar{z}}{a + k_\mu \bar{z}}\right)^{1/2}, \tag{14}$$

where

$$m = -B/2A;\quad f = m^2 + k_G/A;\quad g = m^2 k_\mu;$$

$$k_G = (P_{in}^2 - P_{out}^2)\, d^2F/R\mu_0 T_0 L;\quad k_\mu = \mu_{in}T_{in}/\mu_0 T_0 - 1;$$

$$a = 1 + \frac{d^2F}{d_{in}^2 F_{in}}\,\frac{l_{in}}{L}\,\frac{\mu_{in}T_{in}}{\mu_0 T_0} + \frac{d^2F}{d_{out}^2 F_{out}}\,\frac{L_{out}}{L}.$$

If $\lambda \mathrm{Re} = B$, then we can obtain from (14)

$$G = \frac{k_G}{B}\,\frac{1}{a + k_\mu \bar{z}}. \tag{15}$$

In the particular case for a straight smooth channel $\lambda \mathrm{Re} = 64$. The integral taken in (13) for a law of flow rate variation in the form (14) or (15) causes no special difficulties. Thus, if the flow rate of the cryogenic agent varies in conformity with the dependence (14), then

$$\tau = 1.17\,\frac{Mc_m}{c_p}\,\frac{f - m^2}{8k_\mu m^3}\,\Pi + 52.5\,\frac{Mc_m}{\alpha F_n}, \tag{16}$$

where

$$\Pi = \ln\left|\frac{G_1 - 2m}{G_0 - 2m}\,\frac{G_0}{G_1}\right| + 2m\left[\frac{G_1^2 - G_1 m + 2m^2}{G_1^2(G_1 - 2m)} - \frac{G_0^2 - G_0 m + 2m^2}{G_0^2(G_0 - 2m)}\right].$$

The values of the initial (G_0) and final (G_1) flow rates are determined from (14).

Therefore, by knowing the law of flow-rate variation, the total cooling time can be determined by means of (13) with the final value of the heat-elimination coefficient taken into account. It follows from the results presented that the best cooling mode is the mode P_{in} = const under the condition that the gas productivity by weight of the cryogenic apparatus at the end of the cooling process should equal the capacity of the object. The flow rate of the cryogenic agent exerts the main influence on the cooling time of "long" channels. Hence, to diminish it it is necessary to try to increase the diameter of the heat-transfer-flow-through part of the channel. In the case of short channels, a diminution in the cooling time can be achieved both because of an increase in flow rate and also the heat-transfer intensity. It follows from an analysis of (14) that the delivery and removal piping, performing the function of coupling between the cryogenic apparatus and the object being cooled, play an substantial part here also. The diameter and area of the through sections of this piping should not be less than the corresponding magnitudes of the channel being cooled.

Experiments on cooling a single channel with $L/d \sim 20{,}000$ by gaseous helium passing through a nitrogen bath were conducted to verify the results obtained. The element is in the form of a coil of copper tubing $(4\cdot 0.7)\cdot 10^{-3}$ m with 0.14-m reel diameter. Results of processing the experimental data are presented in Figs. 3 and 4 for the freezing of an element by a constant discharge of cryogenic agent. The total cooling time τ was determined at thermocouple sites at the time of temperature stabilization and not after reaching the cryogenic agent temperature at the entrance to the channel, since despite the careful execution of the test specimen, a heat influx of about 3 W to the latter was observed. It is seen from a comparison of the computed and experimental data that on the whole the dependences proposed for the case $G = \text{const}$ describe the experimental data obtained satisfactorily.

The helium pressure was maintained at $3\cdot 10^5$ N/m² in cooling an element in the $P_{in} = \text{const}$ mode, and the helium temperature at the input to the test element was $T_{in} = 102$°K. The initial temperature of the object was 298°K. The mean value of the output pressure in the experiment was $1.2\cdot 10^5$ N/m². Computation of the channel capacity at the beginning and ending of the cooling process without taking account of the delivery and removal communications ($a = 1$) yields $G_0 = 0.04\cdot 10^{-3}$ kg/sec and $G_1 = 0.133\cdot 10^{-3}$ kg/sec, while $G_0 = 0.038\cdot 10^{-3}$ kg/sec and $G_1 = 0.108\cdot 10^{-3}$ kg/sec if they are taken into account ($a = 1.06$). The same values of the flow rates for a straight smooth channel are $G_0 = 0.071\cdot 10^{-3}$ kg/sec and $G_1 = 0.41\cdot 10^{-3}$ kg/sec. Comparing these flow rates with experimental values ($G_0 = 0.038\cdot 10^{-3}$ kg/sec and $G_1 = 0.076\cdot 10^{-3}$ kg/sec) shows that the best approximation is yielded by the formula that describes the object being cooled most completely. The cooling time of the first period for the three cases considered is, respectively, 43.1, 47.9, and 21.3 min. The experimental cooling time determined upon reaching the temperature 200°K at the end of the channel is 47.8 min. The total cooling time for the element was not determined because of the imperfection of the experimental method.

Satisfactory agreement between the theoretical and experimental results permits recommending the dependences obtained in designing the cooling of single-channel objects.

NOTATION

D, mass of helium in the channel; M, mass of metal of the channel wall; G, mass flow rate of the cryogenic agent; G_{equ}, equivalent mass flow rate; c_p, c_m, mean integrated specific heat of the cryogenic agent and the channel wall material; U, perimeter; τ, cooling time; τ_1, time of the first cooling period; τ_2, time of the second cooling period; Θ, channel wall temperature; T, flow temperature; T_0, initial flow temperature; T_{in}, flow temperature at the channel input; W, flow velocity; L, channel length; L_{in}, L_{out}, lengths of the delivery and removal pipelines; F, F_{in}, F_{out}, cross-sectional areas of the channel being cooled, and of the delivery and removal pipelines; F_s, total heat-transfer surface; d, channel inner diameter; d_{in}, d_{out}, inner delivery and removal pipeline diameters; P, flow pressure; P_{in}, flow pressure at the input to the element; P_{out}, flow pressure at the output from the element; G_0, G_1, initial and final flow rates of the cryogenic agent; z, a coordinate; $\bar{z} = z/L$, a dimensionless coordinate; ζ, dimensionless channel length; η, dimensionless cooling time; V_1, dimensionless temperature; k_G, a, k_μ, f, m, Π, g, parameters; A, B, constants; Re, Reynolds number; R, gas constant; μ, coefficient of dynamic viscosity; λ,, hydraulic drag coefficient; and α, coefficient of heat elimination.

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EFFECT OF TURBULENCE ON THE CHARACTERISTICS OF A GLOW DISCHARGE

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A solution is obtained to the system of equations describing a glow discharge column in a turbulent gas stream. Calculations based on the given theory are found to agree closely enough with experimental data and with calculations made by other authors.

It is well known that turbulization of a flow improves the characteristics of a glow discharge: it allows the temperature of electrons as well as the electric field intensity and the discharge power to be raised, it ensures a higher stability of discharge, etc. [1-3]. It therefore seems worthwhile to develop methods of calculating the characteristics of glow discharge in a gas stream and to establish their dependence on the basic gasdynamic flow parameters. In this study there will be obtained an analytical solution to the problem pertaining to the positive column of such a discharge in a cylindrical channel.

As in the theory of a nonflow positive discharge column with diffusion [4], let the volume recombination be negligible and the temperature of electrons be uniform over the channel cross section with ionization occurring from the ground state of an atom upon collision with one electron. Furthermore, a complete correlation will be assumed [5] between the turbulence characteristics of the atomic gas and those of the ionic gas. The positive column of a glow discharge within the zone of fully turbulent flow can then be described by the equations

$$\frac{1}{Rr}\frac{d}{dr}(r\overline{n'u'}) = \frac{D_a}{R^2 r}\frac{d}{dr}\left(r\frac{d\bar{n}}{dr}\right) + \bar{n}\,\bar{z}_i, \tag{1}$$

$$\bar{n}U_i\bar{z}_i = \varkappa b_e(\bar{n}\,\bar{E}^2 + \bar{n}\,\overline{E'^2} + 2\bar{E}\,\overline{E'n'} + \overline{E'^2 n'}), \tag{2}$$

$$I = 2\pi R^2 e b_e \langle E \rangle \int_0^1 \bar{n} r\, dr \tag{3}$$

under the conditions

$$\bar{n}(1) = n'(1) = 0, \quad \frac{d\bar{n}}{dr}(0) = 0. \tag{4}$$

TABLE 1. Dependence of μ_1 and λ_1 on τ

τ	μ_1	γ_1
0	2,4048	0,2159
—10	1,4487	0,3015
—20	0,7413	0,3735
—30	0,3247	0,4182
—50	0,0461	0,4555

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