AN EXPERIMENTAL STUDY OF HEAT EXCHANGE IN NITROGEN-FREE HELIUM VESSELS WITH A MULTISHIELD SYSTEM OF THERMAL INSULATION

S. B. Mil'man and M. G. Velikanova

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We have investigated the exchange of heat in nitrogen-free helium Dewar vessels with a multishield insulation system, and we have derived the relationship between temperature and the coefficient of thermal conductivity for a multilayers insulation cooled by helium vapors in the temperature range 4.2-293 K.

The development and expanding utilization in cryogenics of effective new thermal-insulation materials and compositions [1] offers opportunities for the development of economical helium vessels with multilayered vacuum-sealed thermal insulation (MVTI), applied directly to the surface of the inside container. Such an approach allows us significantly to simplify the design of the vessel, to reduce its weight, and the difficulty in its fabrication, by eliminating the rigidly heavy nitrogen shield or one cooled by gas, and the need (resulting from such a design) to provide for high reflection characteristics on the part of surfaces facing the vacuum clearance between the vessel and the shield. Of particular interest is the derivation of new data regarding the thermophysical properties of these insulation systems at temperatures below 77 K.

In order to put the finishing touches on the design of this thermal insulation system, in order to study the structure of the heat flows within the vessels, and to measure the relationship between temperature and the coefficient of thermal conductivity in the multilayered vacuum-sealed thermal installation over a temperature range of 4.2-293 K we fabricated and tested experimental SD-30G and SD-100G vessels with respective volumes of 30 and 100 liters.

The SD-30G vessel has a plastic throat with an inside diameter of 60 mm, an operational length of 200 mm, and a wall thickness of 1.2 mm, with a gas permeability factor of $7.5 \cdot 10^{-20}\,m^3 \cdot m(sec \cdot m^2 \cdot Pa)$. The neck of the SD-100G vessel is formed by a tube with diameter 25 × 0.5 mm, a length of 365 mm, and fabricated out of 12Kh18N10T stainless steel. Annealed AD1 aluminum foil was used as the thermal insulation, with a thickness of 7-10 μm, in combination with SNT-10 synthetic paper. The thermal insulation system of the vessels utilized the low temperatures of the vapors of the stored cryogenic fluid, escaping through the neck. It was with this purpose in mind that the MVTI, as it was mounted onto the vessel, was uniformly raised in the neck region to the very top of the working section and it was positioned in close contact to the throat wall. Moreover, in order to elevate the efficiency with which this cold temperature of the vapors was utilized, "soft" shields were uniformly positioned through the thickness of the MVTI. These "soft" shields were in the form of sectional conical pieces of annealed aluminum sheeting with a thickness of 0.8 mm, in tight thermal contact with the throat, and these aluminum pieces were each covered with 2-3 layers of the shielding material.

We used SKT-4 activated carbon as the adsorbent. The SD-30G vessel fabricated out of the aluminum alloy was fitted out with an adsorption pocket in its upper plate, i.e., in the immediate vicinity of the plastic neck which served as the source from which the helium was pumped into the insulated cavity. The adsorption pocket in the SD-100G vessel fabricated out of stainless steel was situated at the bottom plate. The insulation was applied by means of longitudinal-transverse wrapping on a winding apparatus which ensured a constant MVTI packing density. The 60-mm diameter neck was hermetically sealed by means of a cover fitted out with a discharge plug made out of a closed-pore polystyrene foam. The left of the plug was equal to that of the neck, and its diameter was smaller by 1-1.5 mm than the inside diameter of the neck. With this plug it is possible to eliminate the effect of free convection in the neck on the flow of heat to the fluid and improves the exchange of heat between the gas and the wall of the neck. The gas which is formed in the vaporization of the cryogenic fluid passes through the clearance between the neck wall and the plug and through the radial orifices in the upper portion of the latter, entering the nozzle of the gas discharge vent. Three PET-DA fill shields were located in the 25-mm diameter neck.

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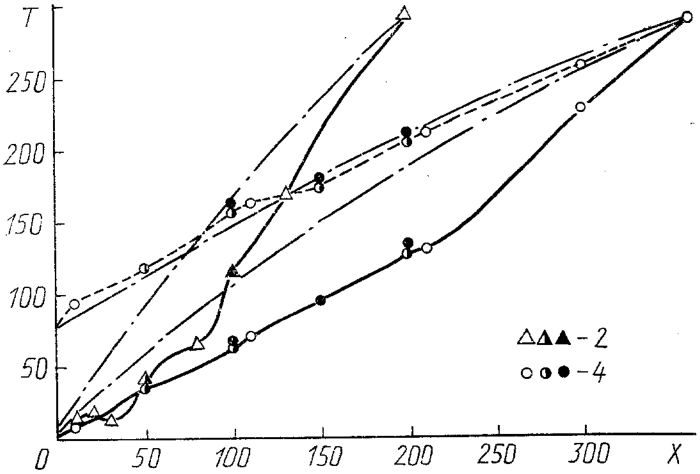

Fig. 1. The temperature T, K of the throat and the shield, as functions of the distance X, mm, and of the cold end of the throat: the open circles represent the temperature at the throat, the circles shaded on the right represent the temperature at the side plates of the shields, and the filled circles identify the temperatures in the middle of the cylindrical portion of the shield (their numerals are identified in Table 1); the solid lines indicate liquid-helium tests while the dashed line represents liquid nitrogen. The dashed-dotted lines show the temperature distribution over the length of the throat where heat is transferred through heat conduction.

TABLE 1. Results of Tests with Liquid Helium and Analysis of Heat-Influx Structure in Experimental Nitrogen-Free Vessels

Item No.	Vessel type	Insulation characteristic					Losses due to vaporization, g/h	Heat influx, W				$\lambda_{eff,av}$, W/(m·K)
		Shield	Lining	Density, cm^{-1}	Thickness, mm	No. of soft shields, pieces		Q_Σ	Q_{ins}	$Q_{v.c}$ formula (1)	$Q_{v.c}$ method [3]	
1	SD-30G	AD1, 7 μm	SNT-10	15	33	3	3,9	0,0217	0,0078	0,0139	—	$1,34 \cdot 10^{-6}$
2	SD-30G	AD1, 10 μm	USNT-10	15	33	3	4,0	0,0227	0,0088	0,0139	0,006	$1,44 \cdot 10^{-6}$
3	SD-30G	AD1, 7 μm	SNT-10	19	43	4	4,6	0,026	0,0096	0,0164	—	$2,0 \cdot 10^{-6}$
4	SD-100G	AD1, 10 μm	SNT-10	21	68	6	5,0	0,028	0,006	0,022	0,038	$8,3 \cdot 10^{-7}$

The vessels were tested with liquid nitrogen and helium in a steady regime by measuring the gas flow rate. The effect of variations in atmospheric pressure on the vaporization was eliminated by use of a cryogenic pressure regulator (barostat) which maintained a constant pressure over the surface of the fluid in the vessel and which was connected in series to a counter. During the course of these tests the temperature distribution was measured in the insulation layer and through the height of the neck by means of manganin–constantan thermocouples in the temperature range 77–293 K and by means of MZhL-MGr1 thermocouples in the range 4.2–77 K.

The characteristics of the tested insulation systems and the results of tests with liquid helium can be found in Table 1. Losses due to vaporization in SD-30G vessels amount, on the average, to 4.2 g/h, which corresponds to 2.5% per day. The somewhat higher vaporization achieved in the SD-30G vessel with four shields is due to the larger number of Teflon-plated thermocouples in the insulation and at the neck.

The magnitude of the losses for the SD-100G vessels amounts to 0.96% per day, which is smaller by approximately 30% than in the standard-series STG-100 vessel, currently in production, with high-vacuum insulation between the first shield and the inside vessel, where the duration of helium filling and loss of fluid during the filling operation are considerably smaller in comparison to the latter.

Of considerable practical interest is the estimation of the quantity of heat flowing to the fluid through the neck that is cooled by vapor and through the insulation of the vessels. In the case of a highly efficient thermal insulation system which makes use of the low temperatures of the vapors passing through the neck for purposes of cooling the MVTI and the soft shields contained within it, when these are in good thermal contact with the neck, we find strong thermal interaction of the latter with the MVTI. In the presence of such interaction the use of experimental and theoretical methods to estimate the magnitude of the flow of heat through the neck, discussed in [2, 3] and based, respectively, on tests with vessels in a nonsteady regime and on the simultaneous solution of the equations of heat conduction for the wall of the neck and the energy for the gas flow in the assumption of the absence of heat exchange to the outside surface of the neck are incorrect. Therefore, in the present study we employed an approach that is based on knowledge of the distribution of temperatures through the height of the neck [1], thus making it possible to find the magnitude of the quantity of heat moving through the neck, by means of the following formula:

$$Q_{v.c} = (\lambda_w f_w + \lambda_p f_p + \lambda_g f_g)\left(\frac{dT}{dX}\right). \tag{1}$$

Having determined the total flow of heat to the inside vessel from the quantity of vaporized fluid and $Q_{v.c}$ from formula (1), we can determine the flow of heat through the insulation:

$$Q_{ins} = Q_\Sigma - Q_{v.c}. \tag{2}$$

Figure 1 shows the distribution of temperatures through the height of the working sections of the throats for the SD-30G and CD-100G vessels. Here we also find plotted the values for the temperatures of the "soft" shields. We can see that the nature of the temperature distribution is different when these throat sections are cooled with nitrogen and helium vapors. In the first case, the measured throat-wall temperatures are virtually the same, while in the second case they are substantially lower than the temperatures (in the corresponding cross sections) than those which the wall would exhibit if the heat were transferred through that wall by means of heat conduction and in the absence of an exchange of heat to the outside and inside surfaces. This illustrates the greater effect of cooling the bridges and the insulation by means of helium vapors as opposed to nitrogen. The temperature profiles in the absence of vapor cooling and exchange of heat with the insulation have been constructed so as to take into consideration the relationship between temperature and the coefficients of thermal conductivity for the materials of these throat sections.

The heat-flow values through the throat section and through the insulation are given in Table 1. We see that 60-80% of the total flow of heat to the fluid is represented by the flow of heat through the throat in the tested vessels. Calculations show that utilization of a plastic throat with a working length of 350 mm and insulation with fixed "soft" shields enables us to reduce the helium losses in the SD-30G vessel by 1.2-1.3% per day, while in the SD-100G vessel by 0.5-0.6% per day.

We can also see from Table 1 that the method [3] yields values of $Q_{v.c}$ different from the experimental data, on the average, by a factor of two. For purposes of comparison we might state that in the tests with liquid nitrogen this difference amounts to 25-30%.

We used the magnitudes of the heat flow through the insulation to determine the average effective thermal conductivity coefficients $\lambda_{eff.av}$ (effective when we take into consideration the utilization of the low vapor temperatures) for the tested multishielded insulation systems. We see that the efficiency of the system with six cooled shields is greater by a factor of 1.5 than in the case of three shields.

The results from tests conducted on vessels with multishielded insulation systems were used to calculate the relationship to temperature in the thermal conductivity of the MVTI made of AD1 aluminum foil and SNT-10 synthetic paper (or USNT-10), applied by a longitudinal-transverse wrapping method, in the temperature range 4.2-293 K. Such data are not available in the literature.

In order to determine this relationship we solved the heat-balance equation system sequentially for those segments which are formed by the shielding between the MVTI and the neck:

$$\lambda_{ins,i}\frac{F_i}{\delta_i}(T_{g,i} - T_{c,i}) + Q_{v.c\,i} = mr + C_p m(T_{c,i} - T_b), \tag{3}$$

where $F_i = \sqrt{F_{h,i} \cdot F_{c,i}}$.

The quantity $Q_{v.c}$ for each neck section is calculated by means of formula (1) in which the derivative $(dT/dX)_{cold}$ is determined at the cold end of the segment on the basis of the temperature distribution at the neck.

The relationship to temperature on the part of the coefficient of thermal conductivity for this composition of the MVTI, cooled by helium vapors, is shown in Fig. 2 and is approximated by the expression

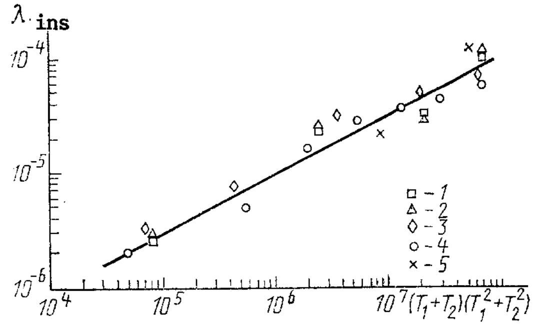

Fig. 2. The coefficient of thermal conductivity λ_{ins}, W/(m·K) for the helium-vapor cooled multilayered vacuum-sealed thermal insulation as a function of the temperature complex $(T_1 + T_2)(T_1^2 + T_2^2)$, K^3 in the temperature range 4.2-293 K: numerals 1-4 correspond to Table 1; 5) results from the TsTG-0.5 tests.

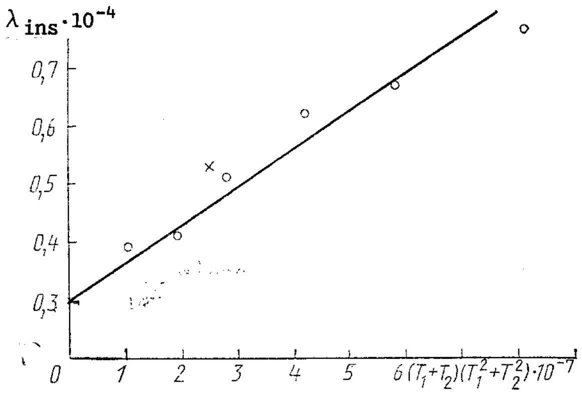

Fig. 3. The coefficient of thermal conductivity λ_{ins}, W/(m·K) for the nitrogen-vapor cooled multilayered vacuum-sealed thermal insulation as a function of the temperature complex $(T_1 + T_2)(T_1^2 + T_2^2)$, K^3, in the temperature range 77-293 K; the notation is the same as in Fig. 2; the line has been plotted on the basis of data from [1].

$$\lambda_{ins} = 8{,}5 \cdot 10^{-9} \sqrt{(T_1 + T_2)(T_1^2 + T_2^2)}. \tag{4}$$

In addition to the data obtained in tests on the SD-30G and SD-100G, Fig. 2 also shows results from the measurements of λ_{ins}, carried out on a TsTG-0.5 liquid-helium experimental tank with a capacity of 500 liters. Its insulation system was made up of a high-vacuum insulation between the inside vessel and the rigid shield suspended at the neck, this latter shield cooled by the discharged vapor, and a multilayered vacuum-sealed thermal insulation made out of AD1 foil and SNT-10 paper was wrapped around this shield, with an embedded "soft" shield. The insulation was accomplished by a method analogous to that employed on the SD vessels. The throat portion of the vessel is formed by a thin-walled tube made out of stainless steel, covered on the outside with plastic. As we can see from the figure, the data derived for variously shaped vessels with different capacities and different types of throat sections are in good agreement with one another and are described by the single relationship (4). An analogous situation is observed for vessels of this type, when tested with liquid nitrogen. Figure 3 shows that the values of λ_{ins}, obtained with SD-100G and TsTG-0.5, are in good agreement with the temperature dependence of this parameter, constructed in [1] from the test results with vessels having a capacity of 30 liters.

The error in the experimental data based on the coefficient of MVTI thermal conductivity does not exceed 15%.

Thus, the results dealt with in the present study demonstrated the possibility of industrial production of economical domestic Dewar helium vessels with a multishielded system of thermal insulation, based on a multilayered vacuum-sealed thermal insulation, in no way inferior in terms of its parameters to the best foreign analogs. An experimental study of the exchange of heat in such vessels for the first time allowed us to obtain the temperature relationship for the coefficient of thermal conductivity in the case of an insulation system fabricated out of AD1 aluminum foil and SNT-10 synthetic paper, applied by the method of longitudinal-transverse wrapping and utilizing the low vapor temperatures of the stored fluid in the temperature interval from 4.2 through 293 K.

NOTATION

Q_{ins}, $Q_{v.c}$, Q_{Σ}, heat flows: through the insulation, through the vapor-cooled throat section, total; λ, coefficient of thermal conductivity; $(dT/dX)_{cold}$, change in temperature at the cold end of the throat section or some segment of the latter; f, lateral cross-sectional area; F, F_h, F_c, surface areas of the insulation: average, hot, and cold boundary surfaces; δ, insulation thickness; T_h, T_c, temperatures of the hot and cold ends of the throat sections; T_1, T_2, boundary temperatures of the insulation layer; m, gas flow rate; r, heat of cryogenic-fluid vaporization; C_p, heat capacity of the gas. Subscripts: ins, insulation; w, wall; pl, plug; g, gas; av.eff, average effective; i, number of throat segments and insulation; b, boiling.

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EFFECT OF INJECTING AN ION BEAM IN A DENSE PLASMA ON THE STRUCTURE OF THE PERTURBED ZONE

V. A. Kotel'nikov and V. P. Demkov

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A hydrodynamic description of a weakly ionized dense plasma with constant properties and frozen-in reactions of formation and the extinction of charged particles serves as the basis for our examination of the influence exerted by the injection of a beam of negative ions on the characteristics of the wall layer.

The study of the interaction of beams of charged particles with a plasma is one of the primary problems confronting plasma physics. The substantial difficulties which arise in the utilization of electron beams, as well as the considerable achievements attained in the development of powerful apparatus for the pulsed generation of strong ion beams, has led to a situation in which greater attention is being devoted to the latter.

We examine the plasma-beam formation restricted by a nonconducting wall into which has been built an electrode whose potential may vary relative to the surrounding plasma. The configuration of the beam-plasma system is shown in Fig. 1.

Let us examine an axisymmetric ion beam propagated through a plasma, parallel to an external magnetic field $B_0 e_z$. If the axial current of the plasma is only partially neutralized by a countercurrent flowing through the plasma, the resulting axial current will generate an intrinsic azimuthal magnetic field $B_\theta^s(r, z)e_\theta$. If, in addition, the space charge of the beam is only partially neutralized by the surrounding plasma, while the electrode is subjected to some potential, then the deviation of the charge from a neutral state will lead to the appearance of radial E_r and axial E_z electric fields.

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