CONTACT HEAT TRANSFER BETWEEN HEAT-LIBERATING ELEMENT AND SURFACE OF SUBLIMING SOLID CRYOAGENT

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The heat transfer in the forced contact of a heat-liberating element with the surface of a subliming solid cryoagent is experimentally investigated. Empirical relations are obtained for the dependence of the heat-transfer coefficient on the heat-flux density in sublimation.

In a number of cases, solid cryoagents — solid nitrogen, argon, carbon dioxide, etc. — are used for heat extraction from a heat-liberating element under cooled or cryostatic conditions. By using solid cryoagents it is possible to extend the operating temperature range of refrigerators and also, in some cases, to reduce their size and weight.

One of the main difficulties in designing such refrigerators is to ensure effective heat transfer from the heat-liberating elements to the solid subliming cryoagent. If no special steps are taken, a layer of vapor forms between the heat-liberating element and the cryoagent [1-3, 5], seriously impairing the heat extraction.

The most effective means of intensifying heat transfer is to create forced contact of the heat-liberating element with the surface of the subliming solid cryoagent by mechanically pressing the heat-liberating element to the surface of the cryoagent (or vice versa). In this case, the minimum thermal resistance is ensured [4].

Since there are no literature data on heat transfer under these conditions, an experimental investigation was carried out using the apparatus illustrated in Fig. 1.

The Dewar flask 1 contains a heat-liberating element 2 in the form of a flat electrical heater and a solid cryoagent 3. The experimental vessel is placed in a protective chamber 4 containing liquid nitrogen or solid carbon dioxide. Heat leakage to the vessel through the cap is reduced by introducing the chamber 5, which acts as a cooled screen. In investigating the heat transfer to solid carbon dioxide chambers, 4 and 5 are also filled with solid carbon dioxide; in the other cases, these chambers are filled with liquid nitrogen.

The heat transfer was investigated for carbon dioxide, neon, para hydrogen, and nitrogen.

The pressure in vessel 1 was held below the triple-point pressure using a VN prevacuum pump.

The solid cryostat in vessel 1 was obtained by evacuating the vapor space above a previously introduced cryogenic liquid [6]. The cryoagent obtained in this way was porous. The carbon dioxide used in the experiments was taken without further treatment from commercial blocks of carbon dioxide for use in the food industry.

TABLE 1. Pore Size and Porosity of Solid Cryoagents

Cryoagent	CO_2	N_2	Ne	p—H_2
Pore size, mm	0,012	0,3	—	1,0
Porosity	0,143	0,19—0,26	~0,25	0,21—0,26

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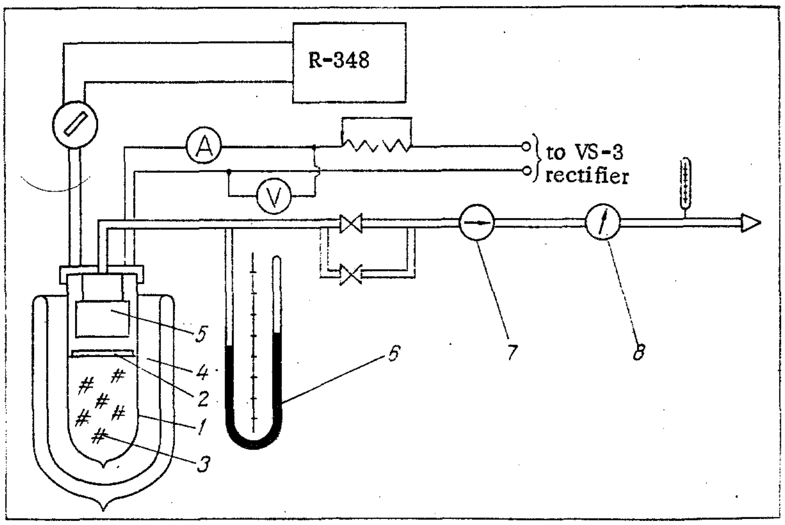

Fig. 1. Experimental apparatus: 1) Dewar vessel; 2) heat-liberating element; 3) solid cryoagent; 4) protective chamber; 5) cooled screen; 6) absolute mercury manometer; 7) vacuum pump; 8) gas meter.

In the experiments measurements were made of the temperature of the solid cryoagent and the heat-liberating element; the amount of sublimed cryoagent; the heat flux transmitted to the solid cryoagent; the level of solid cryoagent in the experimental volume; the pore size of the solid cryoagent; and the force pressing the heat-liberating element to the surface of the cryoagent.

The temperature of the solid cryoagent was determined from the saturation-vapor pressure in the experimental volume by an absolute mercury manometer 6 using a KM-8 cathetometer. In addition, the vapor pressure under the heater surface was measured using a special pressure-sampling instrument.

The temperature of the heat-liberating element was measured using a Cu — Cu + Fe thermocouple calibrated in accordance with VNIIFTRI (All-Union Scientific-Research Institute of Physicotechnical and Radioengineering Measurements) standards in the range 3-300°K. An R-348 potentiometer of class 0.002 was used as the second instrument.

The amount of vapor in the sublimation was measured by a GSB-400 gas meter of class 1, making corrections for pressure and temperature. The heat flux transmitted to the solid cryoagent by the heat-liberating element was measured by an M-1107 instrument of class 0.2. To maintain a stable power output from the heater, a stabilized VS-3 rectifier was used in the supply. The power available at the heater was regulated by a resistance box. The level (and hence the amount) of the solid cryoagent in the experimental volume and the pore size were measured using a KM-8 cathetometer.

In the experiments with nitrogen, as well as for these measurements, the nitrogen concentration was monitored chromatographically and, simultaneously, according to the boiling point of liquid nitrogen at atmospheric pressure. The temperature of the liquid nitrogen was measured by an IS-533 standard platinum resistance thermometer calibrated in the range 20-300°K. The second instrument was an R-348 potentiometer.

The porosities of solid nitrogen and para hydrogen were determined in the course of freezing the corresponding cryogenic liquids on the basis of experimental data on the volumes of the initial liquid at the triple-point temperature and the solid cryoagent and the amount of evacuated vapor. The porosity was 0.14-0.26. The porosity of the solid carbon dioxide was determined by comparing the weights of two blocks of carbon dioxide of the same volume: The weight of unit volume of the carbon-dioxide block used in the experiment was compared with the weight of a block of monolithic structure.

Characteristic results for the pore size and porosity of the cryoagents are shown in Table 1. The characteristic pore size was obtained by calculating the number of pores and determining their dimensions in a layer of solid cryoagent of thickness 10 mm. In each experiment several layers at different levels of the solid cryoagent were taken. The porosities

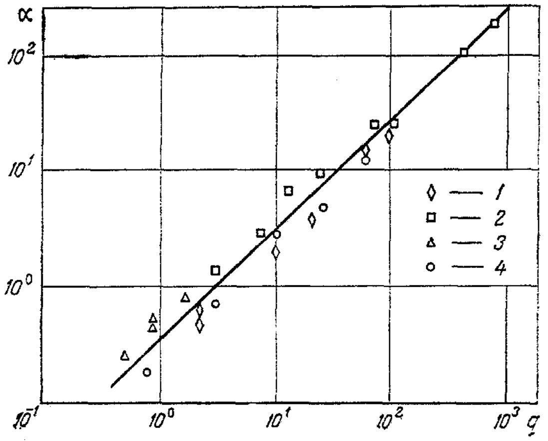

Fig. 2. Dependence of nominal heat-transfer coefficient α on heat-flux density q: 1) carbon dioxide; 2) nitrogen; 3) neon; 4) para hydrogen.

TABLE 2. Empirical Equations for the Nominal Heat-Transfer Coefficient

Cryoagent	$\alpha=f(q)$
Carbon dioxide	$\alpha=0{,}220\ q^{0{,}98}$ (1)
Nitrogen	$\alpha=0{,}553\ q^{0{,}86}$ (2)
Neon	$\alpha=0{,}500\ q^{1{,}01}$ (3)
para Hydrogen	$\alpha=0{,}224\ q^{1{,}01}$ (4)

of nitrogen, neon, and para hydrogen were obtained at bulk evacuation rates, in the course of freezing, of 0.8-1.1 dm^3/min; the total heat supply to the cryoagent was 1.51 W for nitrogen, 0.53 W for neon, and 0.21 W for para hydrogen.

The nominal heat-transfer coefficient α is calculated from the Newton—Richman equations using experimental values of the heat-flux density q and the temperature difference between the heat-liberating element and the cryoagent.

The value of α calculated in this way has a relative error of not more than 3.5%.

The apparent specific pressure of the heat-liberating element on the cryoagent in the experiments was 0.564-67 kN/m^2. No effect of this pressure on the heat-transfer efficiency was observed.

Dependences of α on q obtained by analysis of the experimental data are shown in Table 2. The discrepancy between the experimental α and the values given by Eqs. (1)-(4) does not exceed 2%.

It is possible to approximate Eqs. (1)-(4) for α = f(q) by the equation

$$\bar{\alpha} = 0.376q^{0.905}. \qquad (5)$$

A graph of α = f(q) in logarithmic coordinates is shown in Fig. 2: The line corresponds to Eq. (5) and the points indicate experimental results.

Generalizing the experimental data for all conditions and cryoagents by Eq. (5) leads to an error of not more than 20% when q = 10-1000 W/m^2. When q is small (1-5 W/m^2), the error is larger, reaching 40%. Hence it may be assumed that, because of the difference in thermophysical properties of the cryoagent, the heat-transfer efficiency for heat fluxes q = 10-1000 W/m^2 varies by a factor of not more than 1.2.

On the basis of individual experiments on the effect of porosity on the heat-transfer efficiency, it is possible to assume, as a first approximation, that change in the cryoagent porosity from 0 to 25% has no significant effect on the heat-transfer efficiency. This is because, close to the contact between the heat-transfer surfaces, the cryoagent breaks up to form numerous channels for the evacuation of vapor, in good agreement with the data of [7, 9, 10].

The mechanism of heat and mass transfer in the sublimation of cryoagents under these conditions is very complex. This is because the sublimation is accompanied by considerable increase in volume of the material — by factors of 10^4-10^5 (with respect to the solid phase) [8, 11, 12]. The local vapor velocities are very large and may become supersonic [13].

It may be assumed that under the conditions of the experiments the heat transfer was completely determined by mass transfer. Because the mass-transfer intensity is very large, the thermophysical properties of the cryoagent have practically no effect on the heat transfer. Thus, it may be assumed that heat transfer to any solid cryoagent under analogous conditions would be satisfactorily described by Eq. (5), and hence general relations may be used for calculations of cryostatic systems involving the sublimation of different materials.

Thus, the following conclusions may be made.

1) If forced contact is used in cryostatic systems of sublimation type, the heat-flux density may be varied by 1-2 orders of magnitude in any direction within the range 10-1000 W/m^2 without significant (by 0.2-0.8°) change in the temperature difference and hence in the temperature level of the cryostat.

2) The variation in the nominal heat-transfer coefficient when solid cryoagents with significantly different thermophysical properties are used does not exceed 20% for heat fluxes $q = 10$-$1000\ W/m^2$.

3) By means of the empirical expressions obtained for the nominal heat-transfer coefficient, the heat-transfer surface in active sublimation-type cryostatic systems with different cryoagents may be calculated for a wide range of specific heat fluxes.

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