

EXPERIMENTAL STUDY OF HEAT AND MASS
TRANSFER IN A CRYOGENIC HEAT PIPE

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The operational features of a cryogenic heat pipe are discussed. A description of the experimental device is given, and the experimental results are presented and discussed.

This paper is devoted to an experimental study of heat pipes in which the working fluid is nitrogen.

The operating range of cryogenic heat pipes is limited by the comparatively small temperature range between the critical and triple points. Therefore, the wick of a cryogenic heat pipe must have highly effective thermal conductivity and good thermal contact with the internal wall of the pipe.

An analysis of the known capillary structures such as metal mesh, felt, cermet, longitudinal grooves, and spiral threads with channels showed that the most preferred capillary structures for cryogenic heat pipes are copper wool, ceramics made of sintered metal particles, and a spiral thread combined with a channel. We selected a wick of a sintered bronze powder (Table 1) similar to that used previously [1].

Because of certain features of the technology of powder sintering, the permeability of a wick depends very little on the variation of particle diameter, since there are macropores in the structure in addition to pores commensurate with particle size.

Figure 1a, b are photographs of cross sections of wicks of sintered bronze powder made from particles with diameters 0.2-0.315 and 0.063-0.1 mm, respectively (same magnification). A comparison of these photographs shows that a wick has a broad spectrum of pores of various sizes. The permeability of the wicks studied by us varied insignificantly with variation in the size of the sintered particles, since permeability is mainly determined by macropores.

For the experimental study of a cryogenic heat pipe using liquid nitrogen, a device was built which is shown schematically in Fig. 2. The heat pipe 3 is located in a chamber 1 having a nitrogen shield 2; the chamber walls and the nitrogen shield are separated by the space 13 in which the necessary vacuum is maintained continuously during the time of operation by means of the forevacuum and diffusion pumps 8 and 9 in order to insulate the heat pipe against effects from the environment. The cavity 14 of the nitrogen shield is not connected with the space 13, and a different degree of gas evacuation can be established in it by means of the pumps 6 and 7; this is necessary in order to reduce the heat transfer between the shield

TABLE 1. Characteristics of Wicks Made of Sintered Bronze Powder

Particle diameter, mm	Average particle diameter, mm	Porosity, %	Permeability, m ²	Thermal conductivity, W/m·deg
0,063-0,1	0,081	37,4	2,35·10 ⁻¹⁰	2,69
0,1-0,16	0,13	40,1	2,19·10 ⁻¹⁰	2,64
0,16-0,2	0,18	44,0	2,24·10 ⁻¹⁰	2,93
0,2-0,315	0,26	42,3	2,58·10 ⁻¹⁰	2,97

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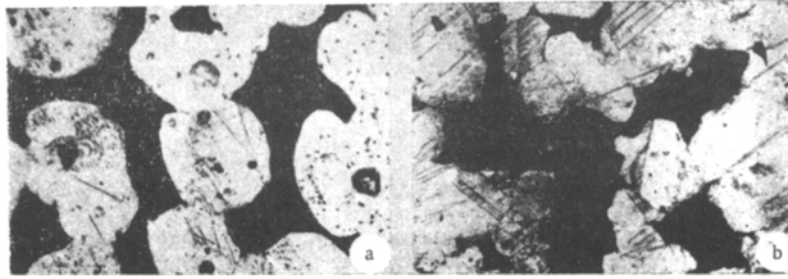


Fig. 1. Cross sections of wicks made of sintered bronze powder with particle sizes 0.2-0.315 (a) and 0.063-0.1 mm (b).

and the surface of the heat pipe. The heat pipe has an electrical heater 4, for which the required powder was measured with a wattmeter, and the heat exchanger 5, which was constantly filled with liquid nitrogen.

The system constructed for charging the heat pipe, like that in [2], consisted of the forevacuum pump 7, the nitrogen tank 10, the charging volume 11, and the manometer 12. Charging was accomplished in the following manner: the charging volume was pumped down together with the internal space of the heat pipe after which it was filled from the tank of nitrogen gas at room temperature and a pressure of 7-10 atm; after the heat pipe had cooled to a temperature for which the gas in the charging volume could be considered heated with respect to the pipe, valve 15 was opened and the nitrogen condensed in the heat pipe. The amount of nitrogen converted to the liquid state was monitored through the drop in pressure by means of the standard manometer 12. The accuracy of the determination of the amount of working fluid in the heat pipe was determined by the accuracy of the measurement of the pressure drop. The charging error did not exceed 6% for a total amount of fluid amounting to 5 g. To monitor operation and measure the temperature drop, six copper — constantan thermocouples, the readings of which were recorded with a P-306 potentiometer, were set up on the housing of the pipe at the positions denoted in Fig. 2.

The experiments were performed with heat pipes having housings made of copper with an external diameter of 12 mm and a wall thickness of 1 mm. The overall length of a heat pipe was 500 mm. The lengths of the evaporation and condensation zones were, respectively, 30 and 50 mm. Heat pipes with wicks of sintered bronze powder having the average particle diameters given in Table 1 were selected for the tests. The diameters of the porous structure (external and internal) were 10 and 8 mm.

The maximum thermal power transported by the heat pipe was determined in the experiments. As it turned out, the maximum thermal power depended significantly on the amount of fluid charge in the heat pipe. Thus, for an amount of fluid needed only for saturation of the wick, the transported power was 4 W for a pipe in a horizontal position (for a heat pipe with a wick of bronze powder with an average particle diameter of 0.18 mm), which is in agreement with a calculation using the expression [5, 6].

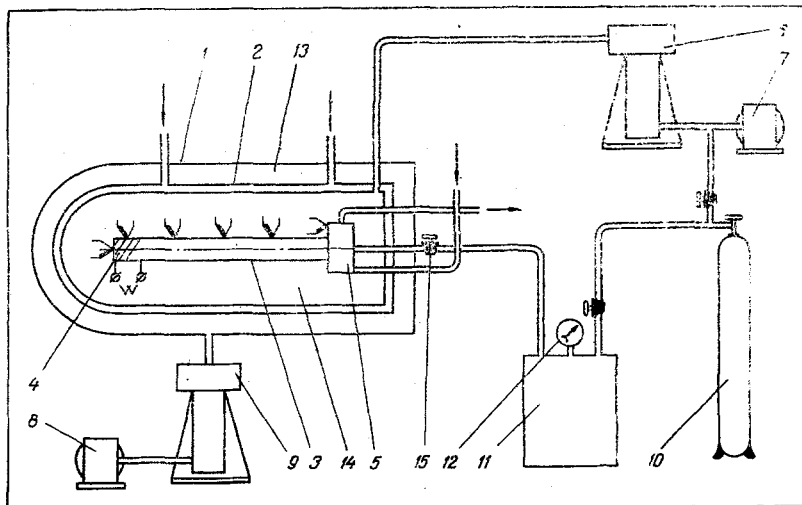


Fig. 2. Experimental device for studying cryogenic heat pipes.

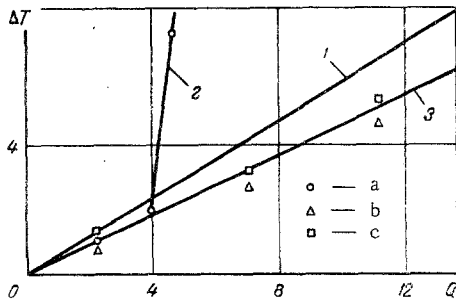


Fig. 3. Dependence of temperature drop between evaporator and condenser of a heat pipe on transported power: 1) theoretical curve; 2) temperature drop in heat pipe for minimum charge; 3) temperature drop in a supercharged heat pipe; a) 5 g N₂; b) 6 g N₂; c) 7 g N₂; ΔT, °C; Q, W.

position of the heat pipe, where the excess fluid accumulated in the lower portion of the vapor channel and did not hinder heat transfer. Overdrying did not develop in the upper portion of the wick, since from the readings of the thermocouples there was sufficient capillary pressure to raise the fluid in the evaporation zone from the lower portion to the upper portion.

Thus, heat pipes with wicks made of sintered bronze powder are of interest for operation in the region of cryogenic temperatures; in this case, they can transport considerable thermal fluxes in the horizontal position for comparatively small temperature drops. It is advisable to introduce a mesh channel in the vapor channel of the heat pipe in order to improve transport characteristics of the wicks.

NOTATION

Q	is the transferred heat flux, W;
σ	is the surface tension, N/m;
K	is the permeability, m ² ;
S _w	is the cross section of the wick, m ² ;
L	is the latent vaporization heat, J/kg;
μ	is the dynamic viscosity, N·sec/m ² ;
ρ	is the density, kg/m ³ ;
l _e	is the evaporator length, m;
l _a	is the adiabatic zone length, m;
l _c	is the condenser length, m;
r _{min}	is the minimum pore radius, m.

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$$Q_{\max} = \frac{2\sigma K S_w L}{\left[\frac{\mu(T_e)}{\rho(T_e)} l_e + \frac{\mu(T_a)}{\rho(T_a)} l_a + \frac{\mu(T_c)}{\rho(T_c)} l_c \right] r_{\min}}$$

The calculated value for the maximum power is 3.6 W.

Nevertheless, despite such positive characteristics of the wicks as high thermal conductivity and capillary potential, the transport characteristics of the wicks turned out to be insufficient for obtaining the optimal characteristics of the heat pipe. This was revealed in experiments to determine Q_{\max} with a small excess of fluid present in the pipe, where its return from the condensation zone to the evaporation zone was accomplished by the action of gravitational force.

The dependence of the temperature drop at the external wall of the heat pipe on transported power was obtained in the experimental studies. This dependence is shown in Fig. 3. The temperature drop along the external wall of the heat pipe both above and below was practically independent of the amount of fluid charge. This result was obtained for a horizontal position of the heat pipe, where the excess fluid accumulated in the lower portion of the vapor channel and did not hinder heat transfer.