EXPERIMENTAL DETERMINATION OF THERMAL
CONDUCTIVITY FOR MATERIALS IN A VACUUM
UNDER VARIOUS LOADS AND AT LOW TEMPERATURES

R. S. Mikhal'chenko and T. A. Kurskaya

We describe the experimental installation and give experimental data on the transfer of heat through a multicontact packet formed of thin plates.

The fraction of the heat influx over the "thermal bridges" in storage and transportation containers for liquefied gases — with ideal heat insulation (screen-vacuum or powder-vacuum) — may amount to more than 50% of the total heat influx to the liquid [1].

The "thermal bridges" include the tubing, the supports, and the suspensions for the internal containers. As is well known, supports must have a certain required strength and be good insulators of heat. One form of a support satisfying this requirement is the multilayer insulating support which may be fabricated in the form of an assembly of thin plates — for axial loads; it can be fabricated in the form of a spiral for radial loads, or it may be made in the form of combined multilayer packets so as to be suitable for any kind of load [2].

Supports of this type are capable of withstanding substantial compressive loads, and the heat influx through these supports as a consequence of thermal resistance at the contacts made by the microirregularities can be reduced many times over in comparison with the influx of heat through a solid material of the same cross section [3].

The transfer of heat through multilayer insulating supports depends on numerous factors: the thermal conductivity and surface characteristics of the basic material, the temperatures of the walls, the pressure magnitudes, and the form of the residual gas between the plate, as well as the mechanical load on the plate.

There are few experimental data on the thermal conductivity of multicontact packets [3-6].

Calculating the thermal resistances of the packets from existing theoretical models — on the basis of formulas for contact heat transfer for two flat surfaces [7] or from the formulas for the specific thermal resistance of a contact pair [6] — yields substantial divergence from experiment. Thus, for example, our comparison of the theoretical data based on the cited theoretical models with the experimental data for the thermal resistances of packets formed by plates with thicknesses of 0.02, 0.1, 0.3, and 0.5 mm from stainless steel and a glass-reinforced KAST Textolite plate 0.25 mm in thickness yielded differences ranging from a factor of 2 through 11 for the 1st model [7] and from 1.5 through 3.5 for the 2nd model [6].

The experimental study of the heat transfer of multicontact plate insulators of various materials in a vacuum and at low temperatures, to obtain their thermal characteristics, as well as the study of the mechanism of heat transfer in such insulators, and its mathematical description, are presently therefore an urgent problem.

Below we describe the experimental installation which basically satisfies the requirements of the above-indicated problem. As an example, we present certain experimental results, derived with this installation for a multicontact stainless steel packet.

Basic Characteristics. 1. The installation is intended for the determination of the effective thermal conductivity of multicontact metallic and nonmetallic specimens formed of plates, for the determination
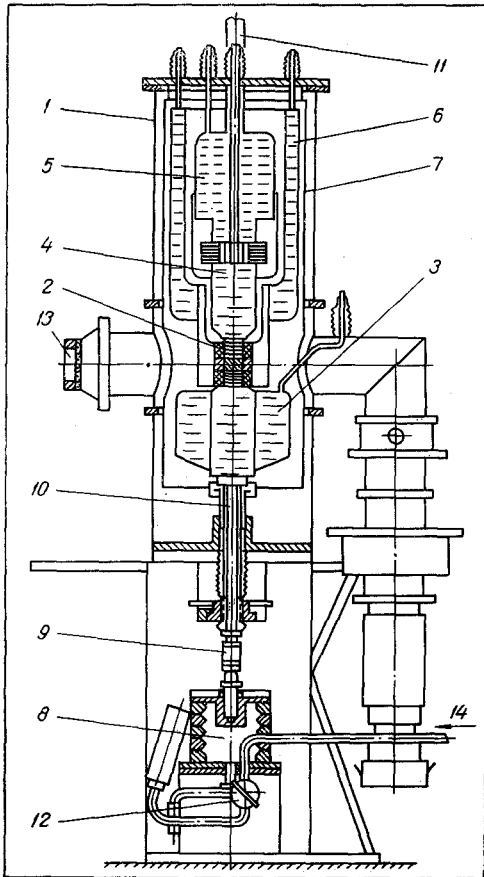
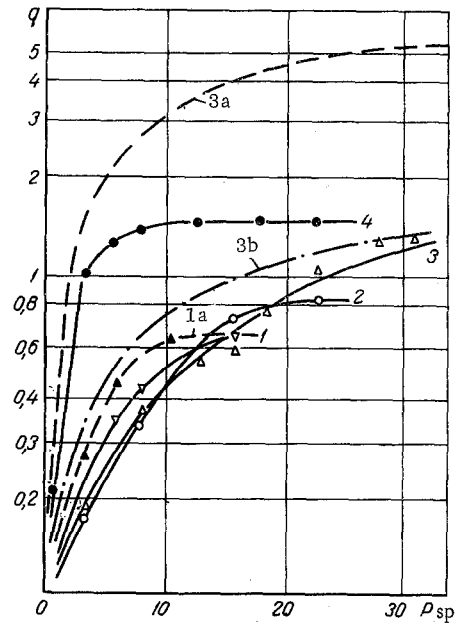Fig. 1. Schematic cross section of the installation.

Fig. 2. Specific heat flow q (W/cm^2) for multicontact and solid specimens as a function of the specific load P_{sp} (MN/m^2) (limit temperatures of 288-77°K): 1,2,3) for 1st, 2nd, and 3rd application of load; 1a) on removal of load; 4) for solid specimen; 3a, 3b) from the formulas given in [7] and [6].

of the thermal conductivity of solid nonmetallic materials, and for the testing of small natural support units with a specific heat flux ranging from 0.001 to 5 W/cm^2.

2. The boundary temperatures range from 363°K to the temperature of the cryogenic liquid used (77 and 20°K), while with use of an electric heater — any temperature within the indicated interval.

3. A static mechanical load can be applied to the specimen: a compressive load from 0 to 9800 N and a tensile load from 0 to 4900 N.

4. Maximum specimen dimensions: diameter, 35 mm; height, 105 mm.

5. Possible displacement of bottom container, with specimen mounted on the container, 35 mm.

6. Maximum rarefaction in the vacuum chamber of the installation, when operating with a nitrogen trap and with hydrogen poured into the containers amounts to $(1-2) \cdot 10^{-5}$ N/m^2.

Construction. The installation (Fig. 1) is made up of a vacuum chamber 1 which contains the specimen 2 (or the specimen with a heater) between the planes of the bottom vessel 3 and the upper measurement-control vessel 4. The latter is protected by vessel 5. Both vessels are protected by the external shielding vessel 6 from extraneous heat influx. All vessels are shielded by means of the heat shield 7.

The System of Static Load on the Specimen. An outstanding feature of this installation, distinguishing it from installations of a similar type [3, 4, 6], is the compact system of static load on the specimen, ensuring high load stability. As the compressed air is fed through conduit 14 from the tank to bellows 8, the bellows rod — whose length can be regulated — through the measuring element 9 (a strain-gauge element or a compression dynamometer) comes into contact with the movable rod 10, transmitting the load to the stress-bearing portion of the bottom vessel 3 and to the specimen in contact with the upper measurement-control vessel 4. The latter is rigidly fixed to the stress-bearing bottom plate of the inside shielding vessel 5 which, in turn, by means of two rods, is fixed to the traverse that is connected by means of columns 11 of the installation. The compressed air is supplied to or removed from the bellows by means of precision control valves 12, to ensure smooth loading or relief of the specimen.

The presence of window 13 in the installation facilitates and makes convenient the insertion and removal of the specimen, as opposed to similar installations of this type.

The evacuation of the chamber and the measurement of the vacuum, the determination of the temperature, and the determination of the heat flow through the specimen are all accomplished in the manner described in [8].

Experimental Error. The overall accuracy with which the thermal conductivity of the specimens is measured by means of the measuring circuit amounts to $\pm 5\%$. However, it should be noted that for small specific loads (below 10 MN/m^2) the experimental results for plate specimens of identical material may differ from each other by approximately 15%. This is explained by the impossibility of reproducing the specimen precisely, because of the differing initial deformation of the plates, as well as because of the various surface structures of plates, even those made from a single lot of sheets.

Experimental Data. The heat flow through the specimens was measured in the installation for a steady-state test regime with respect to the rate of boiling out the cryogenic liquid from the measuring-control vessel. The constant temperature difference across the specimen is achieved by maintaining a specified temperature at the "hot" end of the specimen by pumping the water from the thermostat at a set temperature through the bottom vessel, and the small deviations from the specified temperature (up to 5°) are offset by the electric heater set up on the copper support blocks for the specimen.

The preliminary rarefaction of $(1-2) \cdot 10^{-3}$ N/m^2 in the vacuum chamber was achieved after 6-7 h after switching on the pumping system. The pressure was kept below $6 \cdot 10^{-4}$ N/m^2 throughout the test.

Figure 2 shows the experimental data for the variation in the heat flow as a function of the specific load for a multicontact specimen with a plate thickness of 0.1 mm, made of Cr18N10T—Mo stainless steel in the case of threefold compression of the specimen and these data are compared with the heat flow through a solid specimen and with the theoretical data from the models of [6] and [7].

The specimens were collected between the upper and lower copper bases, into which absolute thermocouples had been imbedded. The specimen height is ≈ 32.5 mm and the diameter is 20 mm. Eight (8) control plates for which the values of R_a (the mean arithmetic deviation of the microirregularity profile, μm) had been determined prior to and after the experiment were positioned uniformly through the height of the specimen; in addition, the profilograms for these control plates were taken prior to the experiment on a "Kalibr-VÉI" profilograph—profilometer. The surface finish of the plate was $\Delta 10$.

The total number of plates in the specimen is 320. The specimen with the bases was placed into the cylindrical polished shielding screen made of thin stainless steel, with a thickness of 0.1 mm and a clearance of 0.9-1 mm about the perimeter. The cold end of the screen was soldered to the copper ring which was connected to the cold wall of the shielding vessel. The electric heater was set up at the hot end of the shield and because of this heater the temperature distribution at the shielding screen was kept close to the temperature distribution through the specimen. The temperature at the cold and hot ends of the screen was measured with the absolute thermocouples attached at the ends of the screen.

In assembling the specimen, the plate surfaces are degreased. No cold welding of the plates was observed; it should be noted that when using multicontact packets of this type in a vacuum, there is no need to be concerned about cold welding. The pressures and the possible surface-deformation mechanisms cannot lead to the cold welding of the plates, provided that foreign films have not been removed from the plate surfaces, i.e., the surfaces have adsorbed layers [9, 10]. However, there is no spontaneous cleansing of the plate surfaces in the above-indicated vacuum [11]. There were no vibrations or displacements of the plates within the packet which would result in the destruction of the surface films in our experiment.

Analysis of the experimental data (Fig. 2) shows that on repeated compression of the specimen (curves 1, 2, 3) the heat flow through the specimen increases by approximately 40-50% at loads in excess of 15 MN /m^2 (the vacuum is retained between the repeated loads). This can be explained by the increase in the area of plate contact with each compression as a consequence of the increasing size of the points of contact and the increase in the number of contact points involved in the transfer of heat. This can also serve to explain the greater values for the heat flow when the load is removed from the specimen, i.e., as opposed to the case in which the specimen is under load (curves 1a and 1, Fig. 2).

Comparison of the heat-flow values for a multicontact specimen (curves 1, 2, 3) with similar data for a solid specimen (curve 4) showed that the multicontact packet substantially reduces flow of heat at specific

loads on the packet of up to 15-20 MN/m². With a load in excess of 30 MN/m², we have, evidently, virtually complete compression of the multicontact specimen and the heat flow through the latter becomes approximately the same as through a solid specimen.

Calculation on the basis of theoretical models [7] (curve 3a) and [6] (curve 3b) demonstrated that better agreement with experiment is offered by the last of the cited models. However, even on the basis of the model from [6], the closest agreement between the theoretical and experimental data (a divergence of 10-20%) is found only for the experimental values of the heat flow derived at substantial compression of the specimen (threefold compression, with specific loads in excess of 20 MN/m² — curve 3).

In conclusion, it should be noted that the divergence between the theoretical data — on the basis of existing theoretical models — and the experimental data is a consequence, in our opinion, of the fact that the working formula recommended by the authors of [7] makes no provision for the thickness of the materials in contact, while the formulas in [6] were derived without consideration of the schematic flow pattern for the heat.

LITERATURE CITED

1. M. G. Kaganer, Thermal Insulation in Low-Temperature Engineering [in Russian], Izd. Mashinostroenie (1966).
2. R. S. Mikhal'chenko et al., "Multilayer insulating support," USSR Patent No. 205842, Priority July 5, 1966, Izobreteniyz, Promyshlennye Obraztsy, Tovarnye Znaki, No. 24 (1967).
3. Maixell and Scott, in: Problems of Deep Cooling [Russian translation], M. P. Malkov (editor), IL (1961).
4. T. R. Thomas and S. D. Probert, Int. J. Heat and Mass Transfer, 9, No. 8 (1966).
5. D. N. Lyon and W. R. Parish, Cryogenics, 7, No. 1 (1967).
6. M. G. Kaganer and R. I. Zhukova, Inzh. Fiz. Zh., 11, No. 3 (1966).
7. Yu. P. Shlykov and E. A. Ganin, Contact Heat Transfer [in Russian], Gosenergoizdat (1963).
8. R. S. Mikhal'chenko et al., Inzh. Fiz. Zh., 11, No. 5 (1966).
9. W. Hofman and I. Z. Ruge, Metallkunde, 43 133-137 (1952).
10. A. P. Semenov, The Seizing of Metals [in Russian], Mashgiz (1958).
11. B. I. Verkin et al., Avtomaticheskaya Svarka, No. 2 (1966).