EXPERIMENTAL STUDY OF THE THERMAL CONDUCTIVITY OF MULTILAYER VACUUM INSULATION

R. S. Mikhal'chenko, A. G. Gerzhin, N. P. Pershin, and L. V. Klipach

Inzhenerno-Fizicheskii Zhurnal, Vol. 12, No. 4, pp. 426–432, 1967

UDC 536.21

The results of an investigation of the most effective multilayer vacuum insulations are presented, and the effect of the structure of fiberglass materials on heat transfer is considered.

In low-temperature engineering the specific heat flow through multilayer vacuum insulation in the stationary regime is usually calculated from the Fourier formula

$$q = \frac{\lambda_{\text{eff}}}{\delta}(T_2 - T_1). \quad (1)$$

In this case, as may be seen from the formula, it is necessary to find λ_{eff} since all the other quantities are known. The heat transfer through this type of insulation may be regarded as depending on the thermal conductivity of the material, radiation, contact resistance, pressure, and the nature of the residual gas. These factors are simultaneously operative, interrelated, variable for each type of insulation, and as yet have no exact mathematical solution.

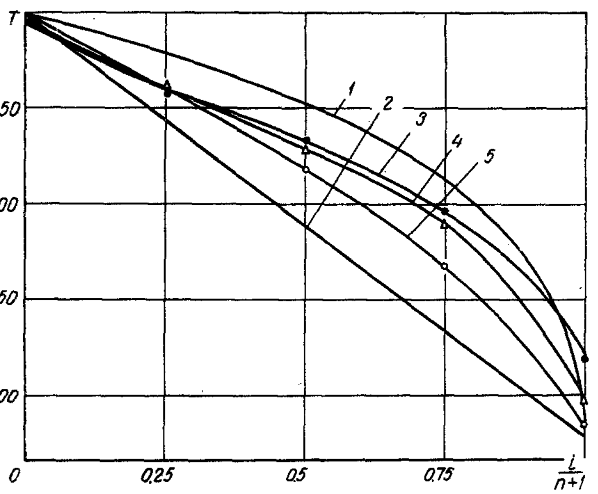

Fig. 1. Distribution of temperature T, °K, over thickness of specimen; 1, 2) according to Eqs. (2) and (3), respectively; 3, 4, 5) aluminum foil + SBR-M glass paper at δ = 40 mm and ρ = 28 screens//cm, 20 and 56, 10 and 12, respectively.

Accordingly, the chief criterion in estimating the heat transfer in multilayer vacuum insulation is a comparison of the experimental data for different types of insulation. A number of authors [2–9] have made experimental studies of the thermal conductivity of multilayer vacuum insulation. The data presented in [5–9] cannot be used directly since domestic insulating materials are not made in the same way as their foreign equivalents.

As for the experimental data presented in [2–4] they are not exhaustive and are insufficient for engineering calculations.

Figure 1 shows the experimental and theoretical temperature distribution in multilayer insulation consisting of sheets of reflective aluminum screens separated by fine-fibered SBR-M glass paper. When the aluminum screens are loosely packed, the proximity of the experimental curve 3 to the theoretical curve 1 based on the Stefan-Boltzmann equation

$$T_i = \left[T_2^4 - \frac{i}{n+1}(T_2^4 - T_1^4)\right]^{1/4} \quad (2)$$

bears witness to the radiative character of the heat transfer in the system. However, as the screen packing density increases, curve 5 approaches the straight line 2 constructed in accordance with the heat conduction equation

$$T_i = T_2 - \frac{i}{n}(T_2 - T_1). \quad (3)$$

Thus, as the packing density increases, the contribution of radiative heat transfer to the over-all heat-transfer balance decreases, while the contribution of heat conduction increases. In [2] Kaganer gives the following formula for λ_{eff} when the screens are loosely packed (assuming heat transfer by radiation only):

$$\lambda_{\text{eff}} = \frac{\delta\varepsilon}{(n+1)(2-\varepsilon)}\sigma_s \frac{T_2^4 - T_1^4}{T_2 - T_1}. \quad (4)$$

The relation between the experimental values λ_{exp} and the theoretical values λ_{theor} in accordance with Eq. (4) for aluminum foil-glass paper insulation with a packing density of 30 screens/cm for the boundary-temperature range 300°–77° K is expressed by the equation

$$\lambda_{\text{exp}} = (3.5 - 4)\lambda_{\text{theor}}. \quad (5)$$

In the calculations the absorption of the screens was assumed to be the same as in [2].

However, a slight change in packing density (see curve 1 in Fig. 2) leads to a considerably greater increase in λ_{eff}.

Thus, the above equation can be used only very approximately and only for finding the order of magnitude of λ_{eff}. The need for further experimental study of multilayer vacuum insulation is obvious.

In practice it is necessary to know how the thermal conductivity varies with the following quantities: a)

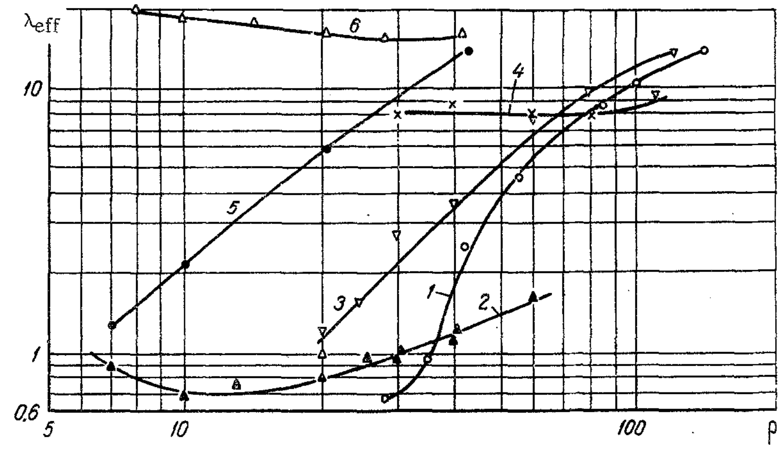

Fig. 2. Effective thermal conductivity λ_{eff}, μW/cm · deg, for several multilayer vacuum insulations as a function of the packing density ρ, screens/cm (T_1 = 77° K, T_2 = 300): 1) 14-μ aluminum foil + + 40-μ SBR-M glass paper; 2) 12.5-μ crumpled aluminized mylar film; 3) the same, corrugated; 4) 40-μ SBR-M without screens; 5) aluminum foil + 150-μ EVTI-15 glass cloth; 6) EVTI-15.

packing density (mechanical compression), b) thickness of insulation, c) variation of boundary temperatures, d) nature and pressure of residual gases.

The thermal conductivity was investigated as a function of these parameters by the flat-plate method in the stationary regime using the calorimetric apparatus described in [1]. Since the effectiveness of different kinds of insulation was established in [2–6], we made a detailed study of the properties of the most effective insulations only. The results of this investigation are presented in Figs. 2–4 and in Tables 1–3.

The insulations were composed of the following materials: a) annealed aluminum foil δ = 14 μ as radiation screens; b) fine-fibered SBR-M glass paper δ = = 40 μ, fiber diameter 5–7 μ, as separating material; c) EVTI glass cloth 150 μ thick, fiber thickness 15–18 μ, as separating material; d) crumpled and corrugated polyethylene terephthalate (mylar) film 12.5 μ thick, with one side surfaced with aluminum 0.025 μ thick.

The investigations were carried out at a vacuum in the calorimeter not lower than 10^{-4} N/m^2, apart from the experiments in which a variation of the vacuum was required.

It is clear from Fig. 2 that the lowest effective thermal conductivity corresponds to the insulation consisting of aluminum screens separated by SBR-M glass paper and crumpled mylar film.

Since heat transfer through the insulation depends on radiation and solid conduction, there must be an optimal packing density at which the over-all heat flow is a minimum. This follows from the fact that radiative heat transfer is proportional to $1/(n + 1)$, while on the other hand, increasing the number of screens per unit thickness leads to a reduction in contact thermal resistance. Starting from a certain value depending on the physical and structural properties of the materials used, the heat conduction increases more than the radiative heat transfer decreases. These remarks are confirmed by the nature of the curves in Fig. 2.

Table 1

Effective Thermal Conductivity as a Function of Insulation Thickness

δ, mm	λ_{eff}, μW/cm· deg	q, μW/cm^2	p, N/m^2
10	1.595	356	$1.2\cdot10^{-4}$
15	1.525	226	$3\cdot10^{-4}$
20	1.685	188	$9\cdot10^{-5}$
28	1.57	125	$3\cdot10^{-5}$

Equation (1) is valid only if λ_{eff} does not depend on the thickness of the insulation. That the thickness has no effect on heat conduction follows directly from the heat conduction equation. This conclusion is confirmed in the first approximation by our experiments at boundary temperatures of 300°–77° K for insulation consisting of aluminum screens separated by SBR-M glass paper, and the results are presented in Table 1. In order to improve the accuracy of the experiment we took the increased packing density ρ = 35 screens/cm (for loose packing ρ = 28 screens/cm).

It should also be noted that λ_{eff} in Eq. (1), being the over-all characteristic of a complex heat transfer process, is valid only in the temperature interval in which it is determined. Accordingly, we made an experimental study of the effect of the boundary temperatures on the heat transfer process. Upon varying the temperature of the cold wall we established that for multilayer vacuum insulation in the temperature intervals 300°–77° K and 300°–20° K

$$\lambda_{eff}\Big|_{20}^{300} = (0.65 - 0.75)\,\lambda_{eff}\Big|_{77}^{300}, \tag{6}$$

while for fiberglass insulation

$$\lambda_{eff}\Big|_{20}^{300} = (0.6 - 0.7)\lambda_{eff}\Big|_{77}^{300}. \tag{7}$$

Table 2

Effect of Insulating Material on Heat Flow Between Surfaces at Temperatures of 300°–77° K

Type of insulation	δ, mm	ρ, layers/cm (screens/cm)	q, $\mu W/cm^2$	$\frac{q_1}{q_i}$
High vacuum, ~ 10^{-4}–10^{-5} N/m2	—	—	4300	1
SBR-M glass paper in vacuum	40	30	444	9.7
EVTI-15 glass cloth in vacuum	40	10	1040	4.13
Aluminum foil + SBR-M glass paper	40	28	52.2	82.5
Aluminum foil + EVTI-15 glass cloth	40	7	85.8	50.2

Table 3

Effective Thermal Conductivities of Various Multilayer Vacuum Insulations

Material	δ, mm	T_2, °K	T_1, °K	ρ, $\frac{\text{screens}}{\text{cm}}$	γ, kg/m^3	λ_{eff}, $\frac{\mu W}{cm \cdot deg}$	p, N/m²
14-μ aluminum foil + + 40-μ SBR-M glass paper	30	300	77 20	28–30	140–150	0.5–0.8 0.35–0.55	$4 \cdot 10^{-5}$ $2 \cdot 10^{-5}$
14-μ aluminum foil + + 150-μ EVTI-15 glass cloth	30	300	77	7–8	42–45	1.1–1.3	$4 \cdot 10^{-5}$
14-μ aluminum foil + +100-μ EVTI-10 glass cloth	30	300	77 20	14–16	80–90	0.7–1 0.5–0.7	$4 \cdot 10^{-5}$ $2 \cdot 10^{-5}$
12.5-μ crumpled mylar film	30	300	77 20	18–22	38–45	0.8–1.1 0.5–0.7	$4 \cdot 10^{-5}$ $2 \cdot 10^{-5}$
12.5-μ corrugated mylar film	30–40	300	77 20	20–25	41–52	1.25–2 0.9–1.5	$4 \cdot 10^{-5}$ $2 \cdot 10^{-5}$
40-μ SBR-M glass paper without screens*	30–40	300	77 20	30–35	35–40	8–9 5–6.5	$4 \cdot 10^{-5}$ $2 \cdot 10^{-5}$
EVTI-15 glass cloth without screens*	40	300	77	10	21	18.8	$4 \cdot 10^{-5}$

*The reduced emissivity of the calorimeter boundary walls was ε = 0.096.

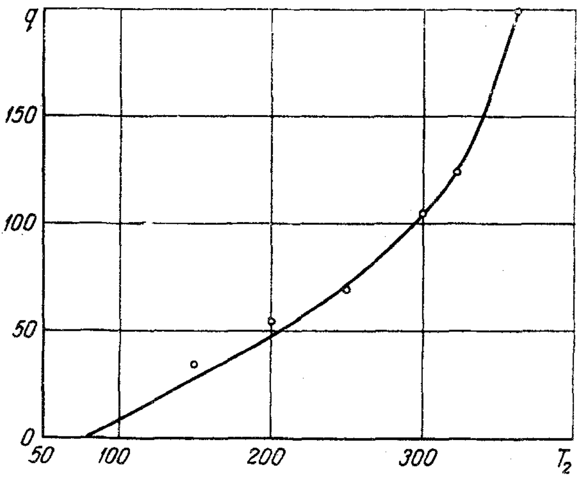

Fig. 3. Specific heat flux q, μW/cm^2, as a function of the hot wall temperature T_2, °K (aluminum foil + + 40-μ SBR-M glass paper, δ = 20 mm, ρ = 28 screens/cm).

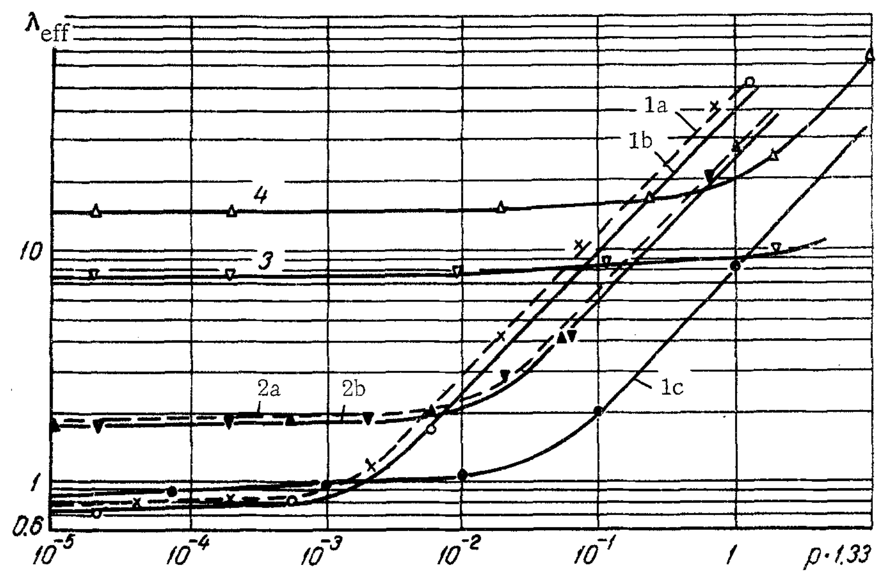

Fig. 4. Effective thermal conductivity λ_{eff}, μW/cm·deg, for certain types of multilayer vacuum insulation as a function of the pressure p, N/m^2, and the nature of the residual gas (T_2 = 300): 1) aluminum foil + SBR-M glass paper, δ = = 40 mm, ρ = 30 screens/cm (a is residual gas hydrogen, T_1 = 20, b is helium, T_1 = 20, c is nitrogen, T_1 = 77); 2) corrugated mylar film, δ = 39, ρ = 25 (a is hydrogen, T_1 = 20, b is helium, T_1 = 20); 3) SBR-M, δ = 20, ρ = 60 layers/cm, nitrogen, T_1 = 77; 4) EVTI-15, δ = 20, ρ = 21, nitrogen, T_1 = 77.

It should also be emphasized that in all the experiments the absolute value of the heat flux in the temperature interval 300°–20° K was less than in the interval 300°–77° K. This effect has also been observed by other authors in connection with both powder-vacuum [11] and screen-vacuum insulation [5]. The explanation of this thermal paradox is still unknown and the investigation of the problem continues.

Figure 3 shows the effect of the temperature of the hot wall on the specific heat flux for insulation consisting of aluminum screens separated by glass paper at a cold wall temperature of 77° K. It is clear from the graph that at temperatures above 250° K the specific heat flux is a function of the fourth power of the hot wall temperature. Thus, at these temperatures the heat transfer through the insulation is mainly due to radiation.

The effect of the materials composing the multilayer vacuum insulation on the total heat flux may be judged from a quantitative comparison of the heat transfer for several types of insulation. All the experiments were performed on loosely packed specimens at boundary temperatures of 300°–77° K. The results are presented in Table 2.

The fact that SBR-M glass paper in an evacuated space reduces the radiant flux by a factor of almost 10, while EVTI-15 glass cloth reduces it by a factor of more than 4, is obviously related with the absorptive and structural characteristics of fiberglass materials.

Whereas the attenuation of the radiant flux can be attributed to the physical nature of the material, the difference in the absolute values of the flux attenuation by glass paper and glass cloth is probably associated only with their structural and technological characteristics. A microscopic examination of glass paper and glass cloth shows that the fiber distribution and the number of fibers per unit area are different. In glass paper with a fiber thickness of 5–7 μ the distribution of the fibers is such that they form a "space lattice" with a dimension of about 15–20 μ, whereas in glass cloth with a fiber thickness of 18–15 μ the corresponding dimension is 100–180 μ. The greater dimensions of the "space lattices" in glass cloth obviously reduce the amount of radiant energy absorbed by the fibers as compared with glass paper. The fiber thickness also affects the absorptivity of fiberglass materials. As the fiber diameter decreases, so does their absorptivity, which is displaced into the longer-wave region of the spectrum above 3μ [10]. In the case considered the radiation spectrum embraces the region 9–35 μ.

Accordingly, in order to obtain maximum efficiency the separating materials should have optimal thickness, fiber diameter, and "space lattice" dimensions.

Introducing reflective screens into packets of glass paper and glass cloth reduced the heat transfer by factors of 8 and 12, respectively. This indicates that in fiberglass materials heat transfer depends mainly on radiation. In spite of the smaller number of screens the reduction of heat flow observed in a glass cloth packet is greater than for glass paper. Thus, the assumption that the greater "space lattice" dimensions of glass cloth make it more transparent to radiation is confirmed.

It is known that the residual gas pressure affects the heat transfer in multilayer vacuum insulation [5,6]. However, the dependence of the heat transfer on the nature of the residual gas in such insulation has not been adequately investigated. The results of experiments to determine the effect of various residual gases on the effective thermal conductivity are presented in Fig. 4. As may be seen from the figure, at a pressure below 10^{-2}–10^{-3} N/m^2 the thermal conductivity reaches a minimum value and is almost independent of the pressure. At pressures above 10^{-2}–10^{-3} N/m^2 the increase in λ_{eff} is directly proportional to the pressure, which is in good agreement with the kinetic theory of gases. For fiberglass materials the residual gas begins to have a significant effect on heat transfer at pressures above 1 N/m^2.

Experimental data on the thermal conductivity of various types of multilayer vacuum insulation are presented in Table 3 (in all cases they relate to loose packing).

NOTATION

q is the specific heat flux; λ_{eff} is the effective thermal conductivity; δ is the thickness of insulation; T_1 is the cold wall temperature; T_2 is the hot wall temperature; T_i is the temperature of the i-th screen; i is the number of the screen; n is the number of screens; ε is the reduced emissivity; σ_s is the Stefan-Boltzmann constant; ρ is the packing density; p is the pressure in calorimeter; γ is the specific weight.

REFERENCES

1. R. S. Mikhal'chenko, A. G. Gerzhin, and N. P. Pershin, IFZh [Journal of Engineering Physics], **11**, no. 5, 1966.

2. M. G. Kaganer, Thermal Insulation Employing a Vacuum [in Russian], TsINTI po avtomatizatsii i mashinostroeniyu, 1963.

3. A. G. Shifel'bain, Tr. VNIIKIMASh, no. 10, 1965.

4. A. I. Moroz, M. G. Kaganer, L. I. Fetisova, and Yu. A. Mirolyubskaya, Kislorodnoe i avtogennoe mashinostroenie, TsINTIKhIMNEFTEMASh, 3, 4, 1965.

5. R. H. Kropschot, J. E. Schrodt, M. M. Fulke, and B. J. Hunter, Adv. in Cryog. Eng., **5**, 199, 1960.

6. M. P. Hnilicka, Adv. in Cryog. Eng., **5**, 199, 1960.

7. P. M. Riede and D. Wang, Adv. in Cryog. Eng., **5**, 209, 1960.

8. L. C. Matsch, Adv. in Cryog. Eng., **7**, 413, 1962.

9. P. E. Glaser, I. A. Black, and P. R. Doherty, Mech. Eng., **T-8**, 23, 1965.

10. E. M. Voronkova, B. N. Grechushnikov, G. I. Distler, and I. P. Petrov, Optical Materials for Infrared Technology [in Russian], izd. Nauka, Moscow, 1965.

11. M. M. Fulke, collection: Problems of Deep Freezing [Russian translation], IL, 1961.

17 September 1966

Physicotechnical Institute
of Low Temperatures,
AS UkrSSR, Khar'kov