6. W. M. Kays, Convective Heat and Mass Transfer, McGraw-Hill, New York (1966).
7. A. V. Lykov, Transfer Phenomena in Capillary Bodies [in Russian], GITTL, Moscow (1954).
8. C. O. Bennett and J. E. Myers, Momentum, Heat and Mass Transfer, McGraw-Hill, New York (1962).
9. Nonsteady Heat Transfer [in Russian], Mashinostroenie (1973).
10. P. J. Schneider, Conduction Heat Transfer, Addison-Wesley, Reading, Massachusetts (1955).
11. P. S. O'Neill, C. F. Gottzman, and J. W. Terbot, Adv. Cryogenic Eng., 17 (1972).
12. P. M. Milton and C. F. Gottzman, Chem. Eng. Progr., 68, No. 9 (1972).

NATURAL THERMAL RADIATION OF HEAT-ABSORBING THERMAL VACUUM CHAMBER SHIELDS

Yu. V. Svetlov, S. P. Gorbachev,
A. I. Skovorodkin, and R. A. Shagiakhmetov

UDC 536.3

A simplified method for computing the natural thermal radiation of heat-absorbing shields of vacuum chambers is elucidated; computational dependences are presented for shields of herringbone outlines and the influence of the geometric profile characteristics on the magnitude of the natural radiation is shown.

The efficiency of the heat-absorbing shield of a thermal vacuum chamber within which is a radiant energy source depends greatly on how small the radiant flux, going into the chamber from the shield is. This flux consists of two components: the reflected radiant flux and the natural thermal radiation of the shield. It is expedient to examine these components separately for a detailed investigation of the influence of the shield on the radiant heat exchange.

In order to assure the requisite absorptivity of the radiant flux, the shields of thermal vacuum chambers are ordinarily set up in the form of a cellular construction. Each individual cell of the shield is a spatial cavity formed either by adjacent shield profiles or by several surfaces of one profile (Fig. 1a).

In the general case, the magnitude of the natural thermal radiation of a cell in the shield is determined by computing the complex (radiant and conductive) heat exchange on the basis of zonal methods, for example, [2, 3]. As a rule, an awkward iteration method of computation is hence used, since the temperature field in

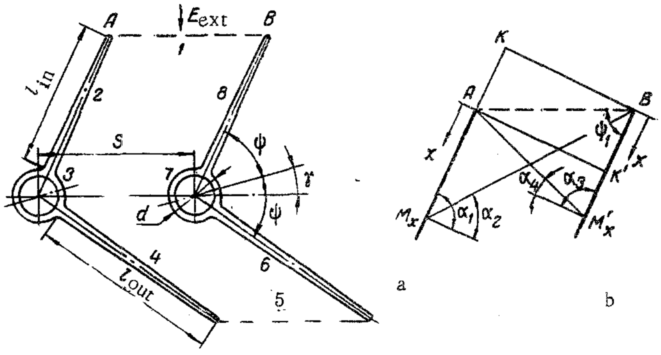

Fig. 1. Cell of a heat-absorbing shield of herringbone profile (a) and analysis of the local angular radiation coefficients from the inner fins of the profile (b).

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 30, No. 2, pp. 317-321, February, 1976. Original article submitted February 25, 1975.

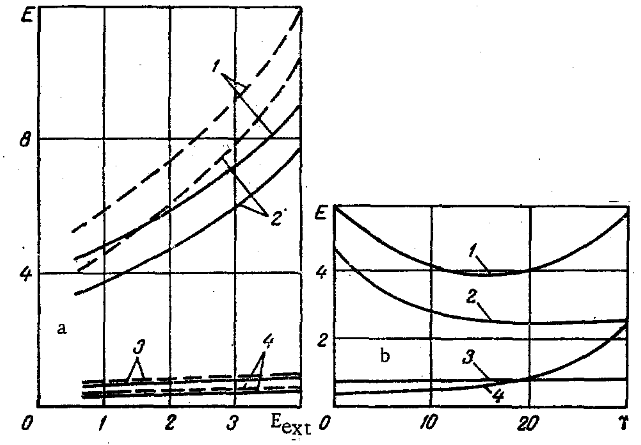

Fig. 2. Dependence of the natural thermal radiation density, E, W/m^2: a) on the external radiation flux density E_{ext}, kW/m^2; b) on the angle of profile rotation γ (1, 2, 3, 4, shield cell, inner fin, cooling channel, outer fin, respectively; solid curves, A = 0.8; dashed curves, A = 0.9).

the profiles, which is unknown in advance, depends not only on the external radiant flux, but also on the distribution of the natural thermal radiation of the surfaces which depends on the temperature field itself.

In a number of cases this problem can be simplified with an accuracy adequate for engineering computations. First, for cooling the shield by a cryogenic coolant (liquid nitrogen, for example) it can be considered that the temperature field in the profiles depends only on the distribution of the external radiant flux. Secondly, taking account of the high absorptivity of the black surface coatings of the profiles which are ordinarily used ($A \geq 0.8$), the natural thermal radiation of the shield surfaces can be considered equal to the sum of just those natural radiation fluxes of the shield surfaces which are incident directly (without rereflection) on the entrance surface of the cell

$$E_c = \frac{1}{F_{en}} \sum_{i=1}^{n} Q_i. \tag{1}$$

It is possible to write for any zone of the profile surface

$$Q_i = \varepsilon_i \sigma \int_{F_i} T_i^4 (M_i) \varphi_{dF_i,\ F_{en}} dF_i. \tag{2}$$

If the surface temperature varies slightly in the zone under consideration, then (2) can be simplified because of the introduction of the mean temperature of the zone surface and, therefore, of the mean angular coefficient of radiation instead of the local coefficient:

$$Q_i = \varepsilon_i \sigma T_i^4 F_i \varphi_{F_i,\ F_{en}}. \tag{3}$$

Therefore, the estimate of the natural thermal radiation of a cell of a heat-absorbing shield is based on determining the temperature fields in the shield elements [1] and a computation of the local or mean angular radiation coefficients.

Let us examine the problem posed in an example of a heat-absorbing shield exposed to an external flux of sufficiently high intensity and which is a grating of herringbone profiles cooled by liquid nitrogen. A cross section of the shield cell partitioned into zones is shown in Fig. 1a: 1 is the entrance surface of the cell; 2 and 8 are inner fins; 4 and 6 are outer fins; 3 and 7 are annular cooling channels; 5 is the exit surface of the shield. In conformity with (1), the natural radiation of the cell is expressed as follows:

$$E_c = \frac{1}{F_{en}} (Q_{in} + Q_{ch} + Q_{out}) = E_{in} + E_{ch} + E_{out}. \tag{4}$$

It can be expected that radiation of the inner fins comprises the main fraction of the natural radiation of the cell. The maximal temperatures and temperature gradients are on these fins; hence, the computation of Q_{in} is carried out by means of the dependence (2) which is written in the following more specific form for

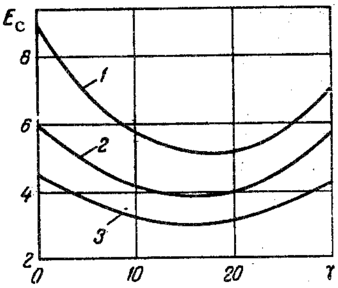

Fig. 3. Influence of the angle of profile radiation E_c, W/m^2, on the natural thermal radiation of a shield cell γ for different E_{ext}: 1) 4 kW/m^2; 2) 2; 3) 0.6 kW/m^2.

this case:

$$Q_{in} = \varepsilon_{in}\sigma \int_0^H \int_0^{l_B} T^4(x, y)(\varphi_{dF_2, F_1} + \varphi_{dF_3, F_1})\, dx\, dy. \qquad (5)$$

It is assumed here that for identical x, the temperature is identical on both sides of the fin.

The transverse dimensions of the cell are usually very much less than the shield length; hence, a dependence for a system extending infinitely in one direction [4] is used to compute the local radiation coefficients:

$$\varphi_{dF_2, F_1} = \frac{1}{2}(\sin\alpha_1 - \sin\alpha_2),\quad \varphi_{dF_3, F_1} = \frac{1}{2}(\sin\alpha_3 - \sin\alpha_4).$$

Taking into account (Fig. 1b) that $\alpha_1 = \alpha_3 = \pi/2$, $\sin\alpha_2 = (M_xK)/(BM_x)$, $\sin\alpha_4 = (M_xK')/(AM_x')$, AB = S, $\psi_1 = \psi + \gamma$, we obtain the computational expressions needed:

$$\varphi_{dF_2, F_1} = \frac{1}{2}\left(1 - \frac{x + S\cos\psi_1}{\sqrt{S^2 + x^2 + 2Sx\cos\psi_1}}\right);$$

$$\varphi_{dF_3, F_1} = \frac{1}{2}\left(1 - \frac{x - S\cos\psi_1}{\sqrt{S^2 + x^2 - 2Sx\cos\psi_1}}\right).$$

For the remaining cell surfaces (outer fins and annular channel), the temperature change in the transverse direction is usually insignificant; hence, the natural thermal radiation of these surfaces can be computed by means of (3). If the temperature along the profile hence varies noticeably, then the dependence T(y) is taken into account, for the outer fin, for example, as follows:

$$Q_{out} = \varepsilon_{out}\sigma l_{out}(\varphi_{F_4, F_1} + \varphi_{F_5, F_1})\int_0^H T^4(y)\, dy. \qquad (6)$$

A computation of the natural radiation of the separate elements and of the cell as a whole in a shield of herringbone profiles with $\psi = 50°$; $\gamma = 0°$; S = 98 mm; d = 40 mm; l_{in} = 85 mm; l_{out} = 120 mm; H = 10 m yields the dependences represented in Fig. 2a. The results obtained confirm the physical representation of the radiant heat-exchange mechanism in the cell, which assumed that the main fraction of the natural radiation is the radiation of the inner fin. The natural radiation of the remaining parts of the profile yields very much less flux, which meanwhile depends slightly on the external radiation.

The angle of rotation γ of the profiles in the shield grating exerts the most substantial influence on the magnitude E_c. Shown in Fig. 2b are the results of computing a cell for diffuse entrance of external flux E_{ext} = 2 kW/m^2, A = 0.8. As is seen, the natural radiation of the annular channel is small and practically independent of rotation of the profiles. Radiation of the inner fin is a maximum at $\gamma = 0$ and diminishes as the profile rotates toward the irradiating flux. At the same time, the radiation of the outer fin grows sharply for large angles of rotation. Consequently, the density of natural thermal radiation of a cell in a shield has a minimum at approximately $\gamma = 15°$. The position of the minimum E_c is practically independent of the magnitude of the external load (Fig. 3). It should be noted that this value of the angle of rotation lies in the range of optimal disposition of the profiles from the viewpoint of thermal shielding of the cryocondensation pump outside the shield grating.

NOTATION

A, integrated hemispherical coefficient of surface absorption; ϵ, integrated hemispherical surface emissivity; Q, radiant flux, W; E, radiant flux density, W/m^2; T, temperature, K; σ Stefan–Boltzmann constant W/m$^2\cdot$K^4; φ, angular radiation coefficient; F, surface area, m^2; ψ, half the angle between the fins of a herringbone profile; γ, angle between the profile axis and the shield surface; S, spacing between profiles, m; H length of the profile fin, m; d, outer diameter of the cooling channel, m; H, shield length, m. Indices: ext, outer; c, shield cell; in, inner fin; out, outer fin; ch, cooling channel; en, entrance surface of the cell.

LITERATURE CITED

1. S. P. Gorbachev, Yu. V. Svetlov, R. A. Shagiakhmetov, and A. I. Skovorodkin, "Cryogenic engineering. Processes in apparatus and systems," Tr. NPO "Kriogenmash," No. 15, 73-85 (1973).
2. Yu. A. Surinov, Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, No. 7, 992-1021 (1953).
3. Yu. A. Surinov, Power Problems [in Russian], Izd. Akad. Nauk SSSR, Moscow, 423-469 (1959).
4. E. M. Sparrow and R. D. Cess, Radiation Heat Transfer, Brooks-Cole (1969).

THERMAL CONDUCTIVITY OF FLUORIDES OF ALKALI EARTH METALS

B. M. Mogilevskii, V. F. Tumnurova, A. F. Chudnovskii, E. D. Kaplan, L. M. Puchkina, and V. M. Reiterov

UDC 536.21

A linear dependence is obtained between the thermal resistance and the temperatures for the monocrystalline fluorides CaF_2, SrF_2, BaF_2, and MgF_2. Anisotropy in MgF_2 has been discovered.

Thermal-conductivity measurements are an efficient method of studying the structural and energy properties of the crystal lattices of a class of ion laser compounds (the alkali earth fluorides) which are important in the practical aspect.

Monocrystals of the alkali earth fluorides are characterized over the range 80-300°K by a linear dependence of thermal resistance on temperature:

$$W = A_1 T + A_2 \tag{1}$$

with a negative value of the constant term A_2 (see Fig. 1a, b, where data of the measurements are given with an error of 5% with respect to steady-state procedure [1]). It is supposed that the negative quantity A_2 is the result of participation in heat transfer of optical branches evolved in the complex structure of fluorite. The coefficient of thermal conductivity can be represented in the form

$$\lambda = W^{-1} = \lambda_{\mathrm{ac}} + \lambda_{\mathrm{opt}} \simeq \frac{B_1}{T} + \frac{B_2}{T^2}, \tag{2}$$

where

$$B_1 = A_1^{-1},\ B_2 = |A_2| \cdot (A_1)^{-2}. \tag{3}$$

The second term in Eq. (2) describes the four-phonon scattering processes of the optical mode, since three-phonon processes for these modes are suppressed because of limitations due to the laws of conservation of energy and momentum [2]. The numerical values of the coefficients A_1 and A_2 for various fluorides with the structure of fluorite in the sequence CaF_2, SrF_2, and BaF_2 are: $A_1 = 0.38 \cdot 10^{-3}$; $0.42 \cdot 10^{-3}$; and $0.6 \cdot 10^{-3}$ m/W; $A_2 = -14.5 \cdot 10^{-3}$; $-18 \cdot 10^{-3}$; and $-21.5 \cdot 10^{-3}$ m·deg/W. The measured values of thermal conductivity in CaF_2, BaF_2, and SrF_2 are higher by approximately 5% than the results of [3, 4], which probably is due to the higher purity of the samples.

In contrast to fluorides with the fluorite structure, MgF_2 has the anisotropic structure of rutile [5-7]. Anisotropy in the directions $\perp$ and $\parallel$ to the optical axis C[001] is manifested by measurements of the elec-

Agrophysical Scientific-Research Institute, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 30, No. 2, pp. 322-327, February, 1976. Original article submitted January 29, 1975.