LOW TEMPERATURE THERMAL INSULATION USING DIFFRACTION EFFECT

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A new type of vacuum layer low temperature thermal insulator is proposed, a reflecting shield which is nontransparent for radiation, having a surface with a regular system of openings. Calculation of the diffraction of the electromagnetic waves allows one to make the total area of the openings close to the area of the shield and thus practically eliminate heat conduction in the insulator by residual gases.

The use of cryogenic apparatus on a continually growing scale in various branches of the economy demands refinement in existing methods and development of new methods and agents for their thermal shielding. Of all the thermal insulators existing at present the most effective is the vacuum layer [1] consisting of a number of reflecting shields having a low degree of blackness, successively spaced in a vacuum housing and thermally isolated from one another.

It is known that in vacuum layer insulators the transfer of heat takes place simultaneously through radiation and gas and solid state conduction. Earlier a majority of investigators assumed that the pressure in the insulator layers did not differ from the pressure in the space surrounding them, therefore at a pressure below $1 \cdot 10^{-4}$-$1 \cdot 10^{-5}$ torr heat transfer by residual gases was ignored. However, in recent years it has been shown [2, 3] that the pressure within the insulator may reach $(5\text{-}8) \cdot 10^{-3}$ torr even at a pressure in the insulator housing below $2 \cdot 10^{-5}$-$1 \cdot 10^{-6}$ torr. Because of this the residual gases* within the layers play an essential role in heat conduction through the insulator vacuum layer. Thus, according to the calculation of the authors of [2] heat conduction by residual gases in an insulator based on aluminum foil and fiberglass paper may reach 70-80%, while in an insulator of PETF crumpled sheeting aluminized on one side it is up to 30-50% of the total thermal flux.

Therefore, to increase the efficiency of an insulator it is necessary to undertake measures allowing one to considerably reduce the pressure within the insulator. This problem can be solved in two ways: either selecting materials with minimal specific gas emission, decreasing the area of the gas emitting surfaces, and treatment with the optimum pregassing technology, or by discovering construction solutions which would allow the creation of favorable conditions for the escape of residual gas molecules. In the first of these a limit is reached, determined by the level of gas emission of existing materials. The known construction solutions also did not produce radical changes. For example, perforation of the shields allows a significant decrease in gas pressure in the insulator layers. Nevertheless the thermal efficiency of the insulator shows practically no improvement in this case [3] because of the increase in radiant heat transfer freely passing through the openings in the shields. A corrugated shield is used in an insulator of the Dymplar type to improve the conditions of escape from the layers. This also does not lead to a decrease in heat conduction of the insulator because of the increase in radiant heat exchange connected with a considerable decrease in the number of shields per unit thickness of the given insulator.

*By the term "residual gases" is meant gases found in the insulator layers due to the dynamic equilibrium of the processes of evacuation and gas emission from the surfaces of the insulator materials.

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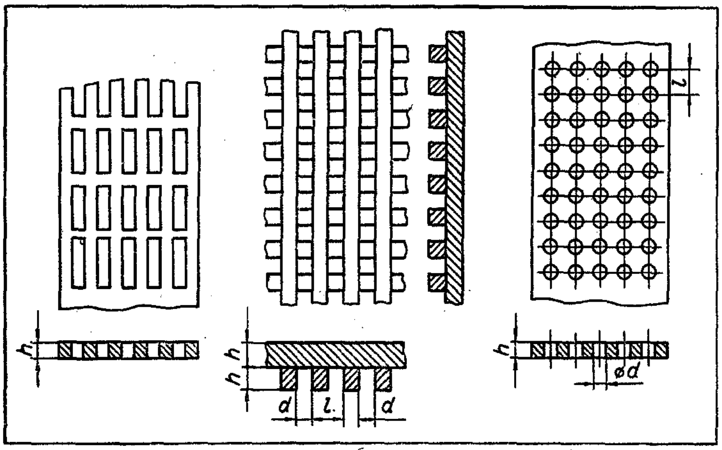

Fig. 1. Examples of construction of perforated diffraction shields.

An insulator construction is proposed in the present work in which one should expect a considerable decrease in heat transfer by residual gases without a significant increase in radiant heat transfer. It will be shown below that taking the effect of diffraction into account allows one to create a shield construction with the total area of the openings close to the full shield area (Fig. 1), which nevertheless reflects practically all the incident radiation.

We also show under what conditions such specific properties of perforated diffraction shields (PDS) are observed.

Usually the radii of shields of vacuum layer thermal insulators considerably exceed the distance between them, which in turn is large in comparison with the maximum wavelength in the infrared range. This circumstance allowed one to consider the reflectors and incident wave fronts to be planes in the solution of the diffraction problem. In addition it was assumed that the perforated shield or two-dimensional diffraction grating reflects unpolarized radiation in the same way as a one-dimensional grating reflects longitudinally polarized waves.

We carried out measurements in the millimeter range (on an instrument from [4] by the method of [5]) of the transmission coefficients of one-dimensional and two-dimensional lattices with a period on the order of the diffracted waves which confirmed the rightness of this assumption. Therefore a numerical solution of the diffraction problem was conducted for the case of normal incidence of an E-polarized wave on a plane reflector consisting of a periodic arrangement of conductors in a perpendicular cross section. The choice of this form of the elements allows one to obtain shields with the desired reflecting characteristics having the largest sized slits for the given range of waves. This is explained by the fact that in obstacles of the waveguide type the properties of a diffraction grating generate a Fourier transformation of the incident radiation supplemented by the filtering properties of a unimodal waveguide.

In this article are presented the dependences of the grating transmission coefficients, expressed in the magnitude of $\overline{b}$, on the relation between their hermetic parameters and the incident wavelength (Figs. 2-4) found through a numerical solution of a double infinite system of linear algebraic equations of the first type, obtained by the method of reseparation into a system of functions complete in the lesser interval [6]. The system of equations describing diffraction effects in structures of the waveguide type, written for the case of longitudinal polarization of the primary field, has the form:

$$2\sum_{n=0}^{\infty} A_n\gamma_m^n\left(1 - ih^*\varphi_m\sqrt{k^2-n^2}\right) = -(1+ikh^*\varphi_m\gamma_m^0\exp(-ikh^*);$$
$$2\sum_{n=0}^{\infty} A_n\delta_m^n = -\delta_m^0\exp(-ikh^*); \tag{1}$$

$$2\sum_{n=0}^{\infty} B_n\gamma_m^n\left(h^*\varphi_m\omega_m^2 - i\sqrt{k^2-n^2}\right) = -(h^*\varphi_m\omega_m^2+ik)\gamma_m^0\exp(-ikh^*);$$
$$2\sum_{n=0}^{\infty} B_n\delta_m^n = -\delta_m^0\exp(-ikh^*);\quad m=1,\ 2,\ 3,\ \ldots, \tag{2}$$

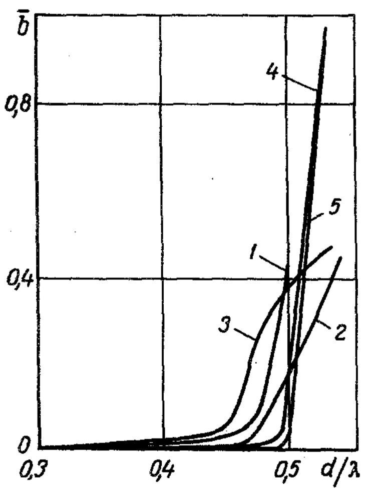

Fig. 2. Change in value of transmission of incident radiation as a function of the ratio between wavelength and dimensions of openings in a one-dimensional lattice for various ratios of its thickness h/l and filling with openings θ ($\bar{b}$ and d/λ are dimensionless): 1) $h/l = 0.5$, $\theta = 0.5$; 2) 1, 0.5; 3) 1, 0.9; 4) 2, 0.9; 5) 4, 0.9.

where

$$\gamma_m^n = \frac{\sin\left(n + \frac{m}{2\theta}\right)\pi\theta}{n + \frac{m}{2\theta}} - (-1)^m \frac{\sin\left(n - \frac{m}{2\theta}\right)\pi\theta}{n - \frac{m}{2\theta}};$$

$$\varphi_m = \frac{\operatorname{th}\omega_m h^*}{\omega_m h^*}; \quad \delta_m^n = (-1)^n \gamma_m^n (1 - \theta);$$

$$\omega_m = \sqrt{\left(\frac{m}{2\theta}\right)^2 - k^2};$$

$$A_n = \begin{cases} a_n - b_n; \\ \frac{a_n - b_n}{2}; \end{cases} \quad B_n = \begin{cases} a_n + b_n; & n = 0; \\ \frac{a_n + b_n}{2}; & n \neq 0. \end{cases}$$

In obtaining the system (1)-(2) the period was taken as equal to 2π. The upper subsystems in (1) and (2) were obtained in "joining" the fields to the slits, the lower by satisfying the boundary conditions on the metal. The systems of equations presented are suitable for a numerical solution on present day PDS with a precision of not less than 1%. The calculated results agree well with experimental data [7].

As seen from Fig. 2, perforated diffraction shields have good transmission properties for all electromagnetic waves having a length more than twice the size of the openings of these structures.† In this case for the wavelengths examined the amount of transmitted radiation can be made as small as desired by increasing the shield thickness.

It is shown in Fig. 3 that the measure $\bar{b}$ of the coefficient of transmission of the incident radiation depends essentially on the degree of filling of the structure with openings θ and is an exponential function of the relative thickness h/l of the PDS.

The concrete choice of geometrical parameters of the PDS is determined by the temperature limits in which the insulator operates. It is known that the spectrum of electromagnetic waves emitted by various surfaces depends on their temperature, and upon its reduction, according to Wien's law, the maximum radiation energy is shifted to the wavelength region ($\lambda_{max}T = 2898\ \mu \cdot °K$). From the distribution of power according to wavelength of electromagnetic radiation for an absolutely black body [8] it follows that at temperatures below 300°K almost all the radiant energy is carried by waves longer than 5μ. Therefore in an insulator operating at temperatures below 300°K the dimensions of the openings in the shields located by the hot wall should not exceed 2-2.5μ. In the cold layers these dimensions may increase in proportion to the decrease in temperature up to 50μ.

†It should be mentioned that the openings may have an arbitrary shape in cross section with the condition that the maximum dimension satisfies the given ratio.

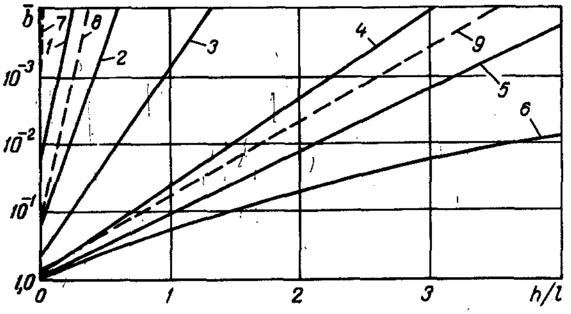

Fig. 3. Dependence of transmission of incident radiation on relative thickness of a one-dimensional lattice for various wavelengths and degrees of filling with openings ($\bar{b}$ and h/l are dimensionless). (Solid lines for k = 0.5; dashed, k = 0.98): 1) θ = 0.3; 2) 0.5; 3) 0.7; 4) 0.9; 5) 0.95; 6) 0.99; 7) 0.1; 8) 0.3; 9) 0.5.

For evacuation of the gas molecules it is desirable that the distance between the openings, i.e., the lattice period, be minimized, although its limiting value will be determined by the technological possibilities of building the structures under examination. While the openings can theoretically occupy up to 99% of the PDS area it should be expected that difficulties in the technology of building such structures will decrease the proportion of openings in the PDS to 20-25%.

The reflective properties of diffraction shields were examined earlier. Below we describe the method of selecting constructive parameters taking into account the characteristics of heat transfer in an insulator in the presence of such shields. In all probability in the proposed insulator heat transfer by gases (as well as in the solid state) is eliminated almost completely. Therefore the choice of shields should proceed from the condition of providing their minimum transmission of radiation and from the existing technological possibilities of producing the smallest of openings.

Because of the magnitude of heat transfer in the insulator by radiation in the absence of openings in the shields, attention must be paid to the proportion of the energy radiated by the hot wall in the short wave region of the spectrum which is relatively free to pass through the PDS (Fig. 4, curves 3 and 5). It should be noted that, as seen from Fig. 4, the short wave radiation ($\lambda < 2d$) will also be blocked by the shield to a certain extent.

We determine what maximum wavelength λ_0 limits the given section of the spectrum. For this one must take into account that the radiation spectrum of real bodies differs considerably from the spectrum of an absolutely black body. The value chosen determines the maximum allowable size of the openings in the PDS located near the hot wall, which is $d < \lambda_0/2$. The minimum period of the distribution of openings will be determined by the technological possibilities of building such structures or by the necessity of gas permeability of the shields, while this in turn is determined by the coefficient of filling of the screens $\theta = d/l$. Making use of the graphs (Fig. 3) and assigning a permissible value of the transmission in the wavelength region of $\lambda > 2d$, it is easy to find the required relative shield thickness h/l from the values of θ and $k = l/\lambda_0$. The calculations show that the thickness of the PDS for a transmission coefficient $\bar{b} \leq 0.1\%$ does not exceed $2l$ in a majority of cases, so that for efficient reflection of radiation in practice it is quite suitable to use aluminum foil 6-20μ thick. We note that the shield may also be made from polymer films covered on both sides with a metal layer having a low degree of blackness.

For thermal separation of the reflecting shields in the proposed construction packing materials are needed having not only a low thermal conductivity but also good gas diffusion and small gas emission. The most suitable materials for this purpose are fiberglass papers manufactured without binders and having elementary fibers 0.3-0.5μ in diameter. In order to assure good gas diffusion the thickness of the fiberglass paper should be minimal and is determined by the technological manufacturing capabilities and the sturdiness required in its use.

In an actual insulator the reflecting shields are separated from each other in space depending on the thickness of the insulator housing. This may cause resonance pumping of energy between neighboring perforated diffraction shields of waves shorter than half the distance between them. However, if $\bar{b}$ is far smaller than the absorption coefficient of such structures for the resonant wavelength, the resonance transmission of energy may be completely disregarded. To show this, consider the process of multiple reflection of waves of unit amplitude between two PDS with identical coefficients of reflection. We obtain a difference in path length for light undergoing m reflections, with intensity decreased by $\bar{a}^{-m}$ times from the field intensity, and emerging from the system with respect to light passing through the two layers without reflection of

$$\Delta = 2m\bar{h}\cos\beta.$$

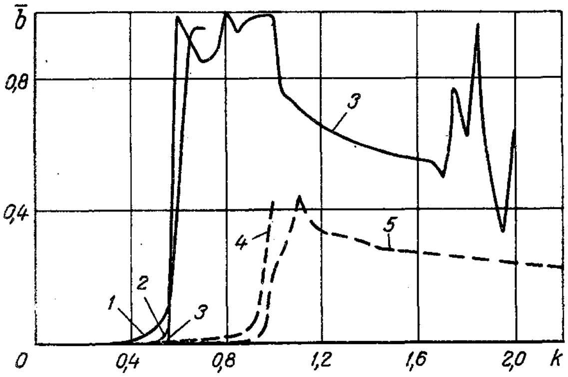

Fig. 4. Dependence of transmission of incident radiation on ratio between period of structure and wavelength for various thicknesses and degrees of openness of lattice (k and $\bar{b}$ are dimensionless) (solid curve, $\theta = 0.9$; dotted, $\theta = 0.5$: 1) h = l; 2) $2l$; 3) $4l$; 5) l.

Here β is the angle of incidence of the wave and $\bar{h}$ is the distance between shields. After the m-th reflection the electromagnetic oscillation has the form

$$\Pi_m = \bar{b}\,\bar{a}^m \exp\left[2\pi i\left(\omega t + \frac{m\Delta}{\lambda}\right)\right], \quad m = 0, 1, 2, \ldots$$

Totalling the entire field of the infinite set of rays passing through the two shields, we obtain

$$\Pi = \sum_{m=0}^{\infty} \Pi_m = \bar{b}\exp(2\pi i\omega t)\left[1 - \bar{a}\exp\left(2\pi i\frac{\Delta}{\lambda}\right)\right]^{-1}.$$

Consequently the field intensity in passing through the two shields can be presented in the form

$$I = \left(1 + \frac{\alpha}{\bar{b}}\right)^{-2}\left[1 + \frac{4\bar{a}}{(1-\bar{a})^2}\sin^2\left(\pi\frac{2\bar{h}\cos\beta}{\lambda}\right)\right]^{-1}, \quad (3)$$

where α is the energetic absorption coefficient, equal to

$$\alpha = 1 - \bar{a} - \bar{b}.$$

It is seen from (3) that in the absence of absorption independently of the value of $\bar{b}$ the plane parallel system is completely transparent for all spectral components having a wavelength $\lambda = 2\bar{h}\cos\beta$. For large intervals between layers this condition can be satisfied for a considerable number of components of the spectrum of incident radiation. However, if $\bar{b} \ll \alpha$ for the shortest of its components the total intensity of the transmitted field is negligibly small.

The calculations made also showed that the transmission of incident radiant energy by the diffraction structures examined changes little when the direction of the incident radiation differs considerably from the normal. Therefore deformation of the shields occurring during packing of the insulation has practically no effect on the value of $\bar{b}$.

Thus, on the basis of the results of an analysis of the mechanism of heat transfer in vacuum layer insulators taking the diffraction effects into account a new type of reflecting shield is proposed in the present article. The use of the PDS leads to only an insignificant increase in radiant heat transfer and allows a considerable decrease in heat transfer by gases in the insulator layers. This leads to a high gas diffusion both in the lining materials and in the reflecting shields, which should lead in the final analysis to a decrease in the total heat flux through such an insulator. The high gas diffusion of the PDS is determined by the fact that in the molecular state the rate of evacuation is proportional to the area of the openings, which in the proposed insulator can comprise up to 20-25% of the total shield area. The reduction in specific weight and the decrease in time and expenditure of cooling agent for its cooling are advantages of the given insulator, while a disadvantage is the complexity of preparing the reflecting shields.

In conclusion it should be noted that up to the present time one possible construction method has been introduced for improving the vacuum in layers of an insulator which consists in the use of perforated shields permeable to radiation. As shown in the present work, other directions in the improvement of gas diffusion consist in the construction of porous vacuum layer insulators having shields impassable for radiation.

NOTATION

l	is the period of the distribution of openings (slits);
$h = 2h^*$	is the thickness of the grating (reflecting shield);
$\theta = d/l$	is the coefficient of filling of the structure with openings;
d	is the diameter of the opening or the width of the slits;
$k = l/\lambda$	is the wave number;
a_n and b_n	are the amplitudes of the Fourier components of the reflected and transmitted fields, respectively;
λ	is the wavelength of the electromagnetic radiation;
β	is the angle of incidence of the wave;
$\bar{h}$	is the distance between the shields;
$\bar{a}$	is the coefficient of reflectivity of the PDS in terms of power.

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