RADIATIVE HEAT TRANSFER BETWEEN INNER PERFORATED CYLINDER AND AN ENTIRE COAXIAL CYLINDER

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An equation for the radiative flux between elements of the system is obtained by the generalized zonal method. Specific features of the heat transfer in a system with a perforated cylinder are discovered and explained.

We consider a system of three coaxial cylindrical surfaces. Two of them — the inner 1 and outer 2 — form the inner cylinder, which has square perforations, while the third is the inside surface of the entire outer cylinder. The temperatures, optical properties, and geometry of the surfaces are prescribed. We require to find the resultant energy flux between the cylinders due to radiative heat transfer.

We make the following assumptions: The cylinders are infinitely long; the surfaces of the cylinders are diffusely gray, optically homogeneous, isothermic, and $T_1 = T_2 > T_3$; the filling medium is diathermic.

We specify the geometry of the system by the parameter $\zeta = D_2/D_3$ (D_2 and D_3 are the cylinder diameters), and the degree of performation of the surfaces of the inner cylinder by the parameter $\beta = F_2/F_2^0$, which is the ratio of the surfaces of the inner cylinder by the to the geometric area F_2^0 of this cylinder.

To the considered system of surfaces we apply the generalized zonal method [1], regarding each surface as a zone.

The relationships for calculating the resultant radiation energy flux Q_{ri} ($i = 1, 2, 3$) of each zone will have the following form:

$$Q_{r1} = -\varepsilon_1\varepsilon_3 E_{23}\gamma_1\gamma_3\varphi_{13}(1-\beta)F_2^0/\Delta, \tag{1}$$

$$Q_{r2} = -\varepsilon_2\varepsilon_3 E_{23}\gamma_3\varphi_{23}(1-\beta)F_2^0/\Delta, \tag{2}$$

$$Q_{r3} = \varepsilon_3 E_{23}\gamma_3(\varepsilon_1\gamma\varphi_{31} + \varepsilon_2\varphi_{32})F_3/\Delta, \tag{3}$$

where

$$E_{23} = \sigma_0(T_2^4 - T_3^4);\quad \Delta = 1 - \gamma_1\gamma_3 R_1 R_3\varphi_{13}\varphi_{31} - \gamma_3 R_2 R_3\varphi_{23}\varphi_{32}$$

and

$$\gamma_1^{-1} = 1 - R_1\varphi_{11};\quad \gamma_3^{-1} = 1 - R_3\varphi_{33};\quad R_i = 1 - \varepsilon_i;$$

ε_i is the emissivity of the corresponding zone.

Of the nine mean angular radiation coefficients (ARC) for this system of surfaces φ_{11} and $\varphi_{23} = 1$ are independent. We found the mean ARC φ_{11} in [2]; it was equal to $1 - \beta$. Then, for the other mean ARC we have, from the equations of closure and reciprocity,

$$\varphi_{13} = \beta;\quad \varphi_{31} = \zeta\beta(1-\beta);\quad \varphi_{32} = \zeta(1-\beta);\quad \varphi_{23} = 1 - \zeta(1-\beta^2). \tag{4}$$

Substituting the obtained values of the mean ARC in relations (1)-(3), we put the expression for the resultant radiative flux from the first and second zones to the third in the form

$$Q_{r(1,2)\to 3} = \frac{\sigma_0(T_2^4 - T_3^4)}{\dfrac{1}{\varepsilon_{\mathrm{eff}1,2}} + \zeta\left(\dfrac{1}{\varepsilon_3} - 1\right)}F_2^0. \tag{5}$$

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The effective emissivity of the perforated cylinder is

$$\varepsilon_{\mathrm{eff}\,1,2} = \varepsilon_2 (1-\beta)\left(1+\frac{\varepsilon_1}{\varepsilon_2}\beta\gamma_1\right), \tag{6}$$

where $\gamma_1^{-1} = \beta + \varepsilon_1(1-\beta)$.

When $\beta = 0$ we find that $\varepsilon_{\mathrm{eff}\ 1,2} = \varepsilon_2$ and Eq. (5) becomes the known equation for the radiative flux between entire coaxial cylinders:

$$Q^0_{r\,2\to3} = \frac{\sigma_0 (T_2^4 - T_3^4)}{\frac{1}{\varepsilon_2} + \zeta\left(\frac{1}{\varepsilon_3} - 1\right)} F_2^0. \tag{7}$$

A comparison of expressions (5) and (7) shows that radiative heat transfer between perforated and entire cylinders is given by the equation for entire cylinders if the emissivity of the entire cylinder in the latter is replaced by the effective emissivity of the perforated cylinder.

The heat transfer between the perforated and entire cylinders exhibits specific features due to the specific features of $\varepsilon_{\mathrm{eff}\ 1,2}$.

The maximum value of the heat flux $Q_{r1,2\to3}$ between the cylinders is attained (for the case $\varepsilon_1 = \varepsilon_2$) at values

$$\beta_{\max} = \frac{\sqrt{\varepsilon(2-\varepsilon)} - \varepsilon(2-\varepsilon)}{(1-\varepsilon)(2-\varepsilon)}, \tag{8}$$

at which function $\varepsilon_{\mathrm{eff}\ 1,2}$ assumes its maximum value. Expression (5), written in dimensionless form,

$$f_1(\zeta, \beta, \varepsilon_i) = Q_{r1,2\to3}/E_{23}F_2^0,$$

is shown (for $\varepsilon_1 = \varepsilon_2$) in Fig. 1. It is apparent that function $f_1(\zeta, \beta, \varepsilon_i)$ has a maximum, which is attained at the values of $\beta_{\max}$ indicated in (8). The curve a in this figure shows $f_1(\beta_{\max})$ for varying values of $\varepsilon_1 = \varepsilon_2$. The figure also shows the existence of a region of values of $\beta(0 \leqslant \beta \leqslant \beta_0$ and $\varepsilon_1 < 1)$ in which the heat flux between the perforated and entire cylinders exceeds the energy flux between entire cylinders.

We find the corresponding values of β_0 from the condition

$$f_2(\zeta, \beta, \varepsilon_i) = \frac{Q_{r1,2\to3}}{Q^0_{r,2\to3}} \geqslant 1, \tag{9}$$

from which we obtain (for $\varepsilon_1 = \varepsilon_2$)

$$\beta_0 = \frac{1-\varepsilon_2}{2-\varepsilon_2}; \quad 0 < \varepsilon_2 < 1. \tag{10}$$

Function $f_1(\zeta, \beta_0, \varepsilon_i)$ is shown in Fig. 1, curve b.

Expression (9) is shown graphically in Fig. 2. It is apparent that the energy flux $Q_{r1,2\to3}$ from the perforated cylinder to the outer entire cylinder may be very much greater than the heat flux between the entire cylinders [by a factor of 2 $(1-\beta)$ when $\varepsilon_2 \to 0$ and $0 < \beta < 0.5$]. When $\varepsilon_1 = \varepsilon_2 = 1$ function $f_2(\zeta, \beta, \varepsilon_1) < 1$ is independent of the values of $\beta > 0$, i.e., in this case a perforated cylinder is energetically less favorable than an entire cylinder.

The specific features of heat transfer between the perforated inner and entire outer cylinders can be attributed to the specific features of the emission of the inner surface of the perforated cylinder. This surface emits an energy flux to the entire cylinder through the small holes, which, as is known, is equivalent to an increase in the emissivity of the radiating surface, i.e., in the radiative energy flux.

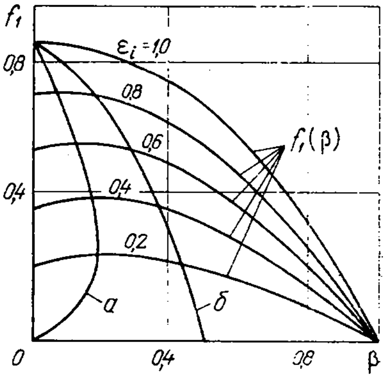

Fig. 1. Functions $f_1(\beta)$ for varying values of β and parameters $\varepsilon_1 = \varepsilon_2$; $f_1(\beta_{max})$ and $f_1(\beta_0)$ for varying values of $\varepsilon_1 = \varepsilon_2$, $\varepsilon_3 = 0.8$; $\zeta = 0.8$.

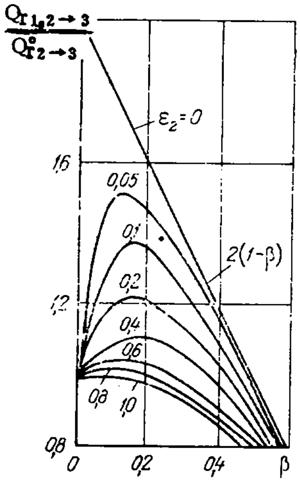

Fig. 2

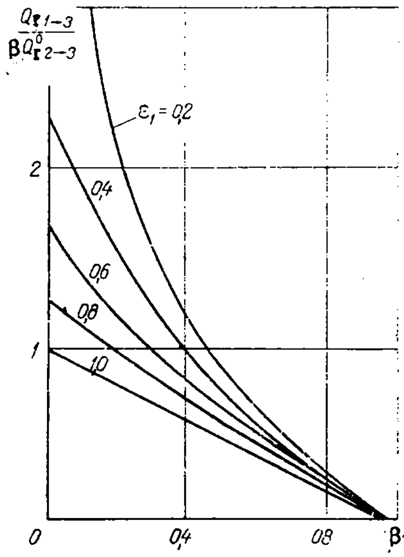

Fig. 3

Fig. 2. Graph of function $f_2(\zeta, \beta, \varepsilon_i)$ for $\varepsilon_1 = \varepsilon_2 = 0.8$; $\zeta = 0.8$.

Fig. 3. Graph of function $f_3(\zeta, \beta, \varepsilon_1)$ for $\varepsilon_1 = \varepsilon_2$, $\varepsilon_3 = 0.8$; $\zeta = 0.8$.

The ratio of the energy flux from the inner surface of the perforated cylinder onto the entire cylinder to the energy flux, which would be radiated onto the entire cylinder by the outer surface of an inner entire cylinder of area β with emissivity ε_1, is given by the function $f_3(\zeta, \beta, \varepsilon_1) = Q_{r1\to3}/\beta Q^o_{r2\to3}$. This function decreases smoothly from the values $f_3(\varepsilon_1, 0, \zeta) = 1/\varepsilon_1$ when $\beta = 0$ (in the case where $\varepsilon_1 = \varepsilon_2$) to zero when $\beta = 1$. The graphs of functions $f_3(\beta, \varepsilon_i, \zeta)$ (Fig. 3) show that there is a region of values of $\beta(\varepsilon_1 < 1)$ in which its values are greater than (or equal to on the boundaries of the region) unity. In this region of values of β the energy flux from the inner surface of the perforated cylinder to the outer cylinder exceeds the energy flux from an entire surface of area βF^o_2. The difference in the emitted fluxes decreases with increase in both β and ε_1, and outside the boundaries of the region decreases from unity to zero.

The contribution of the emission of the inner surface to the total energy flux from the perforated cylinder depends on the relation between the area of the outer surface of the cylinder $(1 - \beta)F^o_2$ and the area of the perforations βF^o_2, through which the inner surface emits. An increase in β leads, on one hand, to a reduction of the effective emissivity of the inner surface of the perforated cylinder and, on the other hand, to an increase in the area of the emitting surface, since βF^o_2 increases. The effect of these factors on the energy flux radiated from the perforated cylinder to the outer cylinder is responsible for the existence of values of β_{max} (ε_i) at which the energy flux becomes a maximum.

In conclusion, we note that the results of [3] are a special case of our general solution of the problem.

NOTATION

T, temperature, °K; ε, total emissivity; D, cylinder diameter; φ_{ik}, mean angular radiation coefficient (ARC); R, reflection coefficient; σ_0, Stefan–Boltzmann constant; ζ, dimensionless parameter, equal to ratio of diameters of coaxial cylinders; F, area of surface; β, ratio of total area of perforations to geometric area of cylinder; β_{max}, values of β at which the radiation energy of the surface is a maximum; β_0, values of β below which the radiation energy of the perforated cylinder is greater than, or equal to, the radiation energy of an entire cylinder; Q_r, resultant radiation flux.

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ANGULAR DEPENDENCE OF EMISSIVITY OF TUNGSTEN IN THE INFRARED REGION OF THE SPECTRUM

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A procedure is described for measuring the angular dependence of the emissivity of metals in the infrared region of the spectrum.

Investigation of the directional radiation properties of materials is of great practical and scientific importance. Experimental data on these properties permit an increase in the accuracy of calculations of radiation heat transfer [1] and are a source of information on the mechanisms of the interaction of light with the surface of a material [2]. The spectral directional radiation properties of materials are of greatest interest, but have been quite inadequately investigated experimentally [3], as shown by the almost complete lack of information on them in the latest handbook [4].

Some results of experimental studies of the angular dependence of the emissivity of metals can be found in [5], but this information is only qualitative. For a long time problems of the quantitative calculation of the spatial distribution of radiation from a heated metal surface remained only a subject of theoretical discussions [6, 7], since there were no reliable data either on the optical constants or on the angular dependence of the emissivity of metals obtained under reproducible conditions of measurement.

It is known that the optical elements of measuring equipment, particularly dispersive systems such as prisms and gratings, are sensitive to the state of polarization of the radiation, as shown by the dependence of their transmission on the polarization parameters of the radiation [8]. Thus, since the degree of polarization of monochromatic radiation from a metal surface varies over wide limits depending on the optical constants of the metal and the angle between the direction of the radiation and the normal to the emitting surface, from now on called the angle of emission, the results of measuring the angular dependence of its emissivity without taking account of the polarization properties of the measuring equipment can turn out to be incorrect.

We have attempted to obtain experimental data on the angular dependence of the emissivity of tungsten at 170°C in the 3.5-10 μm spectral range.

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