CHARACTERISTICS OF THE THERMAL RADIATION OF NONISOThERMAL REGIONS

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Analytical equations are derived which describe a distortion of heat radiation characteristics for gray diffuse and black surfaces, bounded by straight lines or circumferences, with linear and parabolic temperature profiles.

In thermophysical studies based on optical pyrometry with a noncontact determination of characteristic (radiation, color, brightness) temperatures [1], an instability of the radiator temperature [2] can produce appreciable errors. Additional difficulties arise for a nonuniform temperature distribution over the radiating surface area, when a superposition of the radiation characteristics of different-temperature regions brings about uncertainties. It is methodically more complicated to carry out investigations and interpret the measurement results in such cases than in the presence of thermal contrasts between adjacent isothermal regions [3, 4].

The current investigation was aimed at studying the salient features of the radiation characteristics of nonisothermal surfaces, determining the significance criteria of temperature nonuniformities for the simplest configurations of a radiating region with the most typical temperature profiles, correlating the characteristic and surface-average thermodynamic temperatures, and obtaining the effective temperature which defines the radiant energy transfer and characterizes the radiative heat transfer rate.

At the first stage of the investigations, some assumptions and restrictions will be adopted to narrow the range of possible variants of the initial conditions: 1) the radiating surfaces are black or gray diffuse; 2) the regions considered are plane, bounded either by parallel straight lines (a rectangle, an infinite strip) or by a circumference; 3) the observation direction is normal to the plane area and the observation is conducted at a considerable distance, i.e., we assume an almost parallel beam of radiant energy; and 4) temperature distributions of two types are considered, viz., linear and parabolic. Such distributions are typical and can appear in the characteristic heat transfer conditions, i.e., with transverse heat fluxes passing through the section or with a uniform internal heat release. Both processes set up corresponding temperature fields in a stationary thermal mode. Many real situations fall, more or less closely, under the above-stated examples.

1. Let us proceed to considering the heat models of the objects studied (Fig. 1). Spatial orthographic epure projections of linear one-dimensional temperature distributions over a rectangular area (Fig. 1a) and a disk (Fig. 1b) represent the pattern of isotherms depicted by equidistant straight lines.

The temperature distributions in these cases are described by the relations

\[ T(\bar{x}) = T_1 + \frac{\Delta T}{2} (1 - \bar{x}), \quad \bar{x} = \frac{x}{l}, \]  

\[ T(\rho, \varphi) = T_1 + \frac{\Delta T}{2} (1 + \rho \cos \varphi), \quad \rho = \frac{r}{l}, \]  

whereas for parabolic temperature distributions (the epures and patterns of isotherms with all necessary designations are given in Fig. 1c, d) we have, correspondingly,

\[ T(\bar{x}) = T_1 + \Delta T (1 - \bar{x}^2), \]  

\[ T(\rho, \varphi) = T_1 + \Delta T (1 - \rho^2). \]
Equations (1)-(4) pertain to the variants of heat models hereinafter numbered in the adopted sequence — accordingly, variants 1-4.

For the convenience of subsequently using Eqs. (1)-(4) in conformity with the physical meaning of the problem, the initial parameters $T_1$ and $\Delta T$ must be substituted by $T_s$ and $\psi = \Delta T/T_s$ ($T_s$ is the surface-average temperature).

The averaging for variants 1 and 3 is executed by one general equation; likewise, a general representation can be assumed for variants 2 and 4:

$$T_s = \frac{1}{2} \int -1 T(\vec{X}) d\vec{X}, \quad T_\psi = \frac{1}{\pi} \left( \int \int \rho d\rho \right)^{-1} \int \rho T(\rho, \psi) \rho d\rho d\psi.$$  \hspace{1cm} (5)

Integration yields the expression for $T_s$ that is common for all four variants

$$T_s = T_1 + m\Delta T.$$  \hspace{1cm} (6)

The values of $m$ for variants 1-4 are tabulated in Table 1. Having substituted $T_1 = T_s - m\Delta T$ into each of the corresponding Eqs. (1)-(4), we obtain for variants 1-4, accordingly,

$$T(X) = T_s \left( 1 - \frac{\psi}{2} \overline{X} \right), \quad T(\rho, \psi) = T_s \left( 1 + \frac{\psi}{2} \rho \cos \psi \right),$$

$$T(\vec{X}) = T_s \left[ 1 + \frac{\psi}{3} (1 - 3\overline{X}^2) \right], \quad T(\rho) = T_s \left[ 1 + \frac{\psi}{2} (1 - 2\rho^2) \right].$$  \hspace{1cm} (7)

2. We consider the possible ways to describe the heat radiation of areas, starting from the analysis of the spectral radiation flux density, which for the black surface can be represented as [5]

$$I_\lambda = C_1 \lambda^{-5} \left[ \exp \left( \frac{C_2}{\lambda T_X} \right) - 1 \right]^{-1},$$  \hspace{1cm} (8)

where $C_1 = 0.374 \cdot 10^{-5}$ W·m⁻², $C_2 = 1.4388 \cdot 10^{-2}$ m·K, and $T_X$ is the temperature which can be specified in two ways: 1) as the surface-average temperature $T_X = T_s$ and then a certain value of $I_\lambda$, corresponding to the radiation of an isothermal black body with a thermodynamic temperature $T_s$, will be calculated from Eq. (8); 2) as a function of the coordinates, and then $I_\lambda$ will also be predicted as a function of the appropriate coordinates.

In the latter case, determining the effective value $I_{\lambda_{\text{eff}}}$ perceived by a detector at a sufficient distance (when the entire radiating region is observed rather than its individual segments), necessitates a numerical integration of function (8) with respect to the appropriate coordinate (or two coordinates for variant 2), which is an argument of this function, whereas $T_X$ becomes an intermediate parameter.

Of particular interest in the problem being solved is investigating the quantity

$$\delta_\lambda = \frac{I_{\lambda_{\text{eff}}} - I_{\lambda_{\text{eff}}}}{I_{\lambda_{\text{eff}}}}$$  \hspace{1cm} (9)
as a function of $\lambda$, $T_s$, and $\psi$.

Having studied the characteristic of the deviation of the radiation spectrum of a nonisothermal area from the radiation spectrum of an isothermal radiator for a black body, it is possible to extend the deductions to the behavior of the same function $\delta_\lambda(\lambda, T_s, \psi)$ for nonblack bodies since the radiation coefficient in the numerator and the denominator of Eq. (9) is cancelled (if insignificant nonlinearities are neglected).