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MATHEMATICAL MODELING OF RADIANT HEAT EXCHANGE IN THERMOTECHNICAL EQUIPMENT

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An investigation is performed and solution presented of the most general formulation of the problem of radiant heat exchange in a chamber of rectangular cross section filled with an attenuating medium.

Introduction. The present study is an application of the third form of Surinov's generalized zonal method [3-5] to numerical study and solution of the eighth formulation of the problem of [1, 2] of radiant heat exchange in a chamber of rectangular cross section in the shape of a rectangular parallelepiped, filled with an inhomogeneous absorbing and scattering gray medium, the volume V of which is divided along the chamber height into three volume zones V_j ($j = 15, 16, 17$; $V = \sum_{j=15}^{17} V_j$).

The lateral surface of the chamber is divided by the volume zones into three portions each of which consists of four boundary zones. Thus, the boundary surface of the chamber F is divided into 14 zones, two of which, F_{13}, F_{14}, are the chamber bases, while 12 represent the lateral surface. The emissivity A_i ($i = 1, 2, \ldots, 14$) for all these zones, considered as optically homogeneous, diffusely radiating and reflecting gray bodies, is specified.

Formulation of Problem. The eighth formulation of the problem considered below is characterized by a mixed specification of both boundary and internal (volume) optical and energy characteristics of the radiation field. It is required to determine the temperature field for those boundary and volume zones for which the resultant radiant flux has been specified, and to determine the resultant fluxes (and, correspondingly, the densities of the resultant and other forms of hemispherical and volume radiation) for those boundary and volume zones for which the temperature was initially specified.

It will be assumed that for the surfaces F_2, F_6, F_{10}, F_4, F_8, F_{12}, F_{13}, and F_{14} considered as isothermal, the temperatures are specified, while for the remaining boundary surfaces the resultant radiant fluxes are specified and the zones F_1, F_5, and F_9 are considered adiabatic.

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The medium occupying the upper volume zone is purely absorbing ($k_{15} = \alpha_{15}$) and $\eta_{res,15}$ is specified. For the middle volume zone, filled by an absorbing and scattering medium, the temperature T_{16} is specified. The medium filling the bottom volume zone is assumed diathermal ($\eta_{res,17} = 0$).

Calculation Equations. Based on the third form of the generalized zonal method [1-5], the averaged densities of the effective boundary and volume radiation are determined by solution of the following approximate system of linear algebraic equations:

$$E_{ef,i} - \tilde{R}_i \sum_{k=1}^{n} E_{ef,k}\psi_{ik} - \tilde{R}_i \sum_{j=1}^{m} \eta_{ef,j}\rho_{ij} = E_{\alpha,i} \quad (i = 1, 2, \ldots, n), \tag{1}$$

$$\eta_{ef,i} - \varkappa_i \sum_{j=1}^{m} \eta_{ef,j}\rho_{ij}^{(1)} - \varkappa_i \sum_{k=1}^{n} E_{ef,k}\psi_{ik}^{(1)} = \eta_{\alpha,i} \quad (i = 1, 2, \ldots, m). \tag{2}$$

Local characteristics of the incident radiation are determined using the expressions

$$E_{inc}(M_i) = [E_{ef}(M_i) - E_{\alpha,i}]/\tilde{R}_i = \sum_{k=1}^{n} E_{ef,k}\psi(M_i, F_k) + \sum_{j=1}^{m} \eta_{ef,j}\rho(M_i, V_j) \quad (M_i \in F_i;\ i = 1, 2, \ldots, n), \tag{3}$$

$$\eta_{inc}(M_i) = [\eta_{ef}(M_i) - \eta_{\alpha,i}]/\varkappa_i = \sum_{k=1}^{n} E_{ef,k}\psi^{(1)}(M_i, F_k) + \sum_{j=1}^{m} \eta_{ef,j}\rho^{(1)}(M_i, V_j) \quad (M_i \in V_i;\ i = 1, 2, \ldots, m), \tag{4}$$

where n = 14, m = 3; $\tilde{R}_i$, $\varkappa_i$, $E_{\alpha,i}$, $\eta_{\alpha,i}$, generalized boundary and internal characteristics of the radiation; ψ_{ik}, ρ_{ij}, $\psi_{ik}^{(1)}$, and $\rho_{ij}^{(1)}$, generalized mean optical-geometric characteristics of the radiation; $\psi(M_i, F_k)$, $\rho(M_i, V_j)$, $\rho^{(1)}(M_i, V_j)$, $\psi^{(1)}(M_i, F_k)$, generalized local angular coefficients, medium absorptive capabilities, and solid angles, respectively [1-5].

We will introduce the following dimensionless characteristics

$$\theta_{ef,i} = E_{ef,i}/E_{cr};\ q_{ef,j} = \eta_{ef,j}/(4k_jE_{cr}), \tag{5}$$

$$\theta_{inc}(M_i) = E_{inc}(M_i)/E_{cr};\ q_{inc}(M_j) = \eta_{inc}(M_j)/E_{cr}, \tag{6}$$

$$\theta_{inc,i} = E_{inc,i}/E_{cr};\ q_{inc,j} = \eta_{inc,j}/E_{cr}, \tag{7}$$

$$\theta_{\alpha,i} = E_{\alpha,i}/E_{cr} = \begin{cases} A_i\theta_i;\ \theta_i = E_{0,i}/E_{cr}, \\ -\theta_{res,i}\ \ \theta_{res,i} = E_{res,i}/E_{cr}, \end{cases} \tag{8}$$

$$q_{\alpha,j} = \eta_{\alpha,j}/(4k_jE_{cr}) = \begin{cases} \alpha_j\theta_j/k_j;\ \theta_j = E_{0,j}/E_{cr}, \\ -q_{res,j};\ q_{res,j} = \eta_{res,j}/(4k_jE_{cr}), \end{cases} \tag{9}$$

where $E_{cr} = \sigma_0(T_c^4 - T_r^4)$, T_c and T_r are two fixed temperatures from the group of temperatures specified for the boundary and volume zones.

Using Eqs. (5)-(9), the system of equations (1), (2) can be represented in the following dimensionless form:

$$\theta_{ef,i} - \tilde{R}_i \sum_{k=1}^{n} \theta_{ef,k}\psi_{ik} - \tilde{R}_i \sum_{j=1}^{m} q_{ef,j}A_{ij} = \theta_{\alpha,i} \quad (i = 1, 2, \ldots, n), \tag{10}$$

$$q_{ef,i} - \frac{\varkappa_i}{4k_i} \sum_{k=1}^{n} \theta_{ef,k}\psi_{ik}^{(1)} - \frac{\varkappa_i}{4k_i} \sum_{j=1}^{m} q_{ef,j}A_{ij}^{(1)} = q_{\alpha,i} \quad (i = 1, 2, \ldots, m), \tag{11}$$

while Eqs. (3), (4) take on the form

$$\theta_{inc}(M_i) = \sum_{k=1}^{n} \theta_{ef,k}\psi(M_i, F_k) + \sum_{j=1}^{m} q_{ef,j}A(M_i, V_j) \quad (M_i \in F_i;\ i = 1, 2, \ldots, n), \tag{12}$$

$$q_{inc}(M_i) = \sum_{k=1}^{n} \theta_{ef,k}\psi^{(1)}(M_i, F_k) + \sum_{j=1}^{m} q_{ef,j}A^{(1)}(M_i, V_j)\ (M_i \in V_i;\ i = 1, 2, \ldots, m). \tag{13}$$

Moreover, we have

$$\theta_{inc,i} = \sum_{k=1}^{n} \theta_{ef,k}\psi_{ik} + \sum_{j=1}^{m} q_{ef,j}A_{ij}\ (i = 1, 2, \ldots, n), \tag{14}$$

$$q_{inc,i} = \sum_{k=1}^{n} \theta_{ef,k}\psi_{ik}^{(1)} + \sum_{j=1}^{m} q_{ef,j}A_{ij}^{(1)}\ (i = 1, 2, \ldots, m). \tag{15}$$

In Eqs. (10)-(15) we make use of relationships relating the various characteristics of the medium absorbing capability

$$A_{ij} = 4k_j\rho_{ij};\ A(M_i, V_j) = 4k_j\rho(M_i, V_j),$$
$$A_{ij}^{(1)} = 4k_j\rho_{ij}^{(1)};\ A^{(1)}(M_i, V_j) = 4k_j\rho^{(1)}(M_i, V_j). \tag{16}$$

The required boundary local and mean energy characteristics are determined on the basis of the following expressions:

a) for zones with specified temperature θ_i

$$\theta_{res}(M_i) = A_i[\theta_{inc}(M_i) - \theta_i],\ \theta_{res,i} = A_i(\theta_{inc,i} - \theta_i)\ (M_i \in F_i;\ i = 1, 2, \ldots, n); \tag{17}$$

b) for zones with specified resultant flux $Q_{res,i} = F_iE_{res,i}$

$$\theta(M_i) = \theta_{inc}(M_i) - \theta_{res,i}/A_i;\ \theta_i = \theta_{inc,i} - \theta_{res,i}/A_i\ \ (M_i \in F_i;\ i = 1, 2, \ldots, n). \tag{18}$$

Determination of the volume local and mean energy characteristics of the radiation is accomplished with the following relationships:

a) for zones with specified temperature θ_j

$$q_{res}(M_j) = \frac{\alpha_j}{4k_j}\ [q_{inc}(M_j) - 4\theta_j];\ q_{res,j} = \frac{\alpha_j}{4k_j}\ [q_{inc,j} - 4\theta_j]\ (M_j \in V_j;\ j = 1, 2, \ldots, m); \tag{19}$$

b) for zones with specified resultant volume radiation density $\eta_{res,j}$

$$\theta(M_j) = \frac{1}{4}\ q_{inc}(M_j) - \frac{k_j}{\alpha_j}\ q_{res,j}\ \theta_j = \frac{1}{4}\ q_{inc,j} - \frac{k_j}{\alpha_j}\ q_{res,j} \tag{20}$$
$$(M_j \in V_j;\ j = 1, 2, \ldots, m).$$

Thus, the solution of the problem formulated reduces to sequential determination and calculation of the following radiation characteristics:

local generalized optical-geometric radiation characteristics $\psi(M_i, F_k)$, $\rho(M_i, V_s)$ (or $A(M_i, V_s)$), $\psi^{(1)}(M_j, F_k)$ and $\rho^{(1)}(M_j, V_s)$, (or $A^{(1)}(M_j, V_s)$) for $M_i \in F_i$, $M_j \in V_j$, i, k = 1, 2, ..., n; j, s = 1, 2, ..., m;

mean generalized optical-geometric radiation characteristics ψ_{ik}, ρ_{is} (or A_{is}), $\psi_{jk}^{(1)}$, $\rho_{js}^{(1)}$ (or $A_{js}^{(1)}$) for i, k = 1, 2, ..., n; j, s = 1, 2, ..., m;

average local (boundary and volume) dimensionless densities of effective, incident, and resultant radiation based on Eqs. (10), (11), and Eqs. (12)-(20).

The most difficult part of the solution is the determination of local and average generalized optical-geometric radiation characteristics, because of the need to calculate various multiple integrals.

Determination of Local and Mean Generalized Optical-Geometric Radiation Characteristics. In the equations for local and mean generalized optical-geometric radiation characteristics [1-6], there appears an exponential function $\exp[-h(M_i, N_k)]$, where $h(M_i, N_k)$ is the optical thickness of the layer of medium, defined by the expression

$$h(M_i, N_k) = \int_0^{r(M_i, N_k)} k(r)\, dr.$$

In the case of a homogeneous medium ($k(r) = \text{const}$) we have $h(M_i, N_k) = kr(M_i, N_k)$.

For an optically inhomogeneous medium, the medium extinction coefficient $k(M)$ is a function of the point, varying along a ray between points M_i and N_k. Assuming that the medium is inhomogeneous only along the z coordinate (the vertical), introducing the variables $z = r\cdot \cos\gamma + z_i$, $dz = \cos\gamma dr$, $\cos\gamma = (z_k - z_i)/r(M_i, N_k)$, we obtain

$$h(M_i, N_k) = \int_0^{r(M_i, N_k)} k(r)\, dr = \frac{1}{\cos\gamma} \int_{z_i}^{r(M_i, N_k)\cos\gamma + z_i} k(z)\, dz = \frac{r(M_i, N_k)}{z_k - z_i} \int_{z_i}^{z_k} k(z)\, dz = k_{av}(M_i, N_k)\, r(M_i, N_k),$$

where

$$k_{av}(M_i, N_k) = \frac{1}{z_k - z_i} \int_{z_i}^{z_k} k(z)\, dz.$$

To calculate local generalized radiation coefficients, the conventional trapezoid method is used, together with the closure equation and the condition of symmetry for corresponding subsystems of the given radiating system. We note that two additional zones F_{18} and F_{19} were introduced here, dividing the volumes V_{15}, V_{16}, and V_{17}.

In calculating the mean generalized radiation characteristics, Korobov's method [7] was used for integrals having no singularities, while Korobov's method in combination with that of Gauss was used for integrals with singularities. Also widely used were reciprocity equations of the form [3]

$$\psi_{ik} F_i = \psi_{ki} F_k;\ \psi_{ik}^{(1)} V_i = 4 F_k \rho_{ki},$$

together with the closure equation and the condition of symmetry for individual subsystems of the radiating system.

The validity of these radiation characteristic calculations was verified by use of the closure equation for the entire radiating system, and also by comparison of the calculated results with data from the literature (Detkov–Vinogradov table [6]).

Example. We will consider a concrete chamber with dimensions $a = 1$, $b = 1.5$, $h = 3$. The height of the volume zones V_j will be identical, $h_1 = h_2 = h_3 = 1$.

The following dimensional and dimensionless parameter values will be specified for boundary and volume zones: $\theta_{res,1} = \theta_{res,5} = \theta_{res,9} = 0$; $\theta_{res,3} = \theta_{res,7} = \theta_{res,11} = 0.01$; $T_2 = T_6 = T_{10} = 600°K$ (corresponding dimensionless values $\theta_2 = \theta_6 = \theta_{10} = 0.019853$); $T_4 = T_8 = T_{12} = 800°K$ (dimensionless $\theta_4 = \theta_8 = \theta_{12} = 0.062745$); the base temperature $T_{13} = 1000°K$, $T_{14} = 400°K$ (dimensionless $\theta_{13} = 0.153186$ and $\theta_{14} = 0.003922$); $q_{res,15} = 0.02$; $T_{16} = 1600°K$ ($\theta_{16} \doteq 1.003922$); $q_{res,17} = 0$.

In the given case the dimensionless radiation characteristics are the ratios of the corresponding dimensional characteristics to the quantity $E_{cr} = E_{16,14} = \sigma_0(T_{16}^4 - T_{14}^4)$.

The boundary surfaces are assumed optically homogeneous with emissivities equal to $A_i = 0.8$ ($i = 1, 2, \ldots, 14$).

For the volume zones the values $\alpha_{15} = k_{15} = 0.5$ [1/m]; $k_{16} = 1$ [1/m]; $\alpha_{16} = \beta_{16} = 0.5$ [1/m]; $k_{17} = \alpha_{17} = \beta_{17} = 0$ were chosen.

Analysis of Numerical Results. The numerical calculations performed and a study of various average generalized optical-geometric characteristics of the radiation in this chamber produced the following dependence of these characteristics on coordinates x, y, and z.

Figure 1 shows the z dependence of local absorptive capability $A^{(1)}(M, V_{15})$, $A^{(1)}(M, V_{16})$ of the volume zones V_{15} and V_{16} at inner points of the chamber. With displacement of

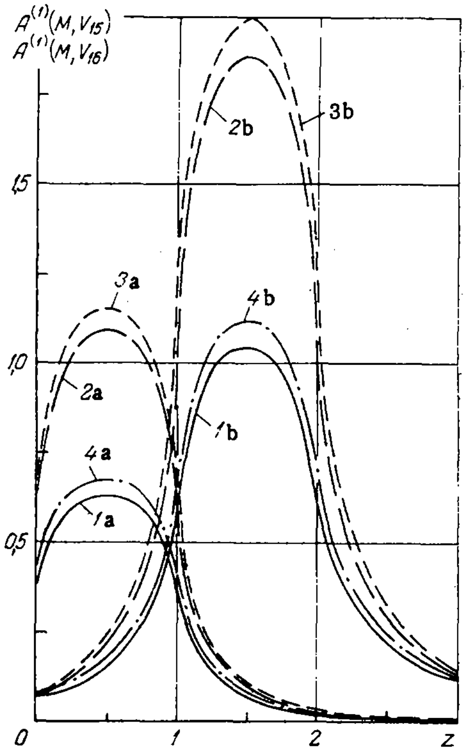

Fig. 1

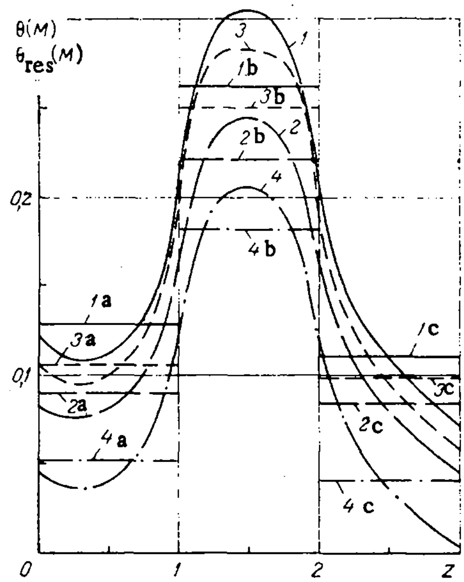

Fig. 2

Fig. 1. $A^{(1)}(M, V_{15})$ and $A^{(1)}(M, V_{16})$ vs z ($M \in V_{15}$, V_{16}, V_{17}): a) $A^{(1)}(M, V_{15})$; b) $A^{(1)}(M, V_{16})$; 1) $\bar{x} = 0.5$; $\bar{y} = 0$; 2) $\bar{x} = 0.5$; $\bar{y} = 0.25$; 3) $\bar{x} = \bar{y} = 0.5$; 4) $\bar{x} = 0$; $\bar{y} = 0.5$ ($\bar{x} = x/a$; $\bar{y} = y/b$).

Fig. 2. Dimensionless temperatures $\theta(M_i)$, θ_i and surface resultant radiation density $\theta_{res}(M_i)$, $\theta_{res,i}$ vs z at midpoint of chamber lateral surface: 1) x = 0.5a, y = 0; 2) x = a; y = 0.5 b; 3) x = 0.5a; y = b; 4) x = 0, y = 0.5b; a) i = 1, 2, 3, 4; b) i = 5, 6, 7, 8; c) i = 9, 10, 11, 12.

points $M \in V$ along the vertical from the upper to the lower boundary $A^{(1)}(M, V_{15})$ first increases, taking a maximum value at $z = h_1/2$ (~1.3 for $x/a = y/b = 0.5$) then falls off, reaching values of 0.04-0.06 at $z = h_1 + h_2$ and 0.02 at $z = h$.

For $A^{(1)}(M, V_{16})$ there is a more significant change with z coordinate. As for $A^{(1)}(M, V_{17})$ in the given case, this quantity is identically equal to zero, since the zone V_{17} is diathermal.

Figures 2-4 show results of a numerical study of the distributions of boundary and volume energy characteristics on the lateral surface and in two volume zones of the chamber.

Figure 2 presents the z dependence of radiation energy characteristics on the chamber lateral surface in four planes. In particular, for the zones F_1, F_5, F_9 and F_3, F_7, F_{11}, curves of dimensionless temperature on the median verticals of the respective faces are shown. For the surfaces F_2, F_6, F_{10} and F_4, F_8, F_{12}, the distribution of resultant radiation surface density on median verticals of the corresponding faces is shown. The same figure depicts mean values of the energy characteristics for corresponding zones of the lateral surface.

The dependence of the energy characteristics on the other coordinates x, y, or the z dependence with different fixed values of x, y differs greatly.

Figure 3 shows $q_{res}(M_{16})$ as a function of coordinates x, y, z within volume zone V_{16}. It is evident that the dependence of $q_{res}(M_{16})$ on z and x is identical in character. Also shown is the mean value of $q_{res,16}$.

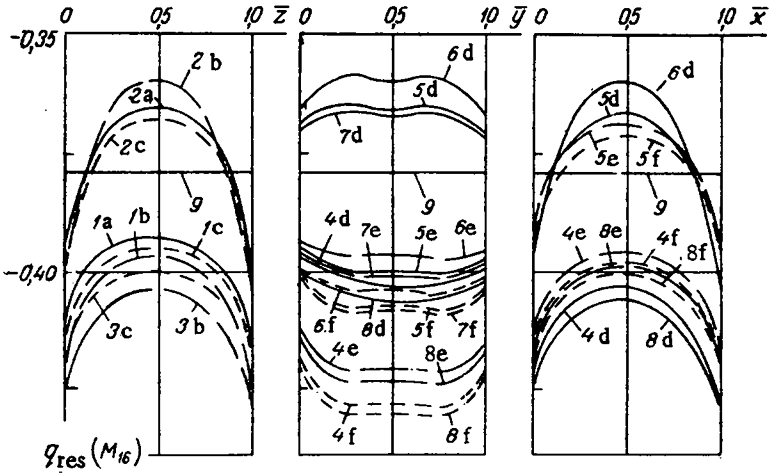

Fig. 3. $q_{res}(M_{16})$ vs coordinates $\bar{x}$, $\bar{y}$, $\bar{z}$: 1) x = 0; 2) x = 0.5a; 3) x = a; 4) z = h_1; 5) z = h_1 + 0.25 h_2; 6) z = h_1 + 0.5 h_2; 7) z = h_1 + 0.75 h_2; 8) z = h_1 + h_2; 9) $q_{res,16}$;

a) y = 0; b) y = 0.5b; c) y = b; d) $\bar{x}(\bar{y})$ = 0.5; e) $\bar{x}(\bar{y})$ = 0; f) $\bar{x}(\bar{y})$ = 1 ($\bar{x}$ = x/a; $\bar{y}$ = y/b; $\bar{z}$ = (z − h_1)/h_2).

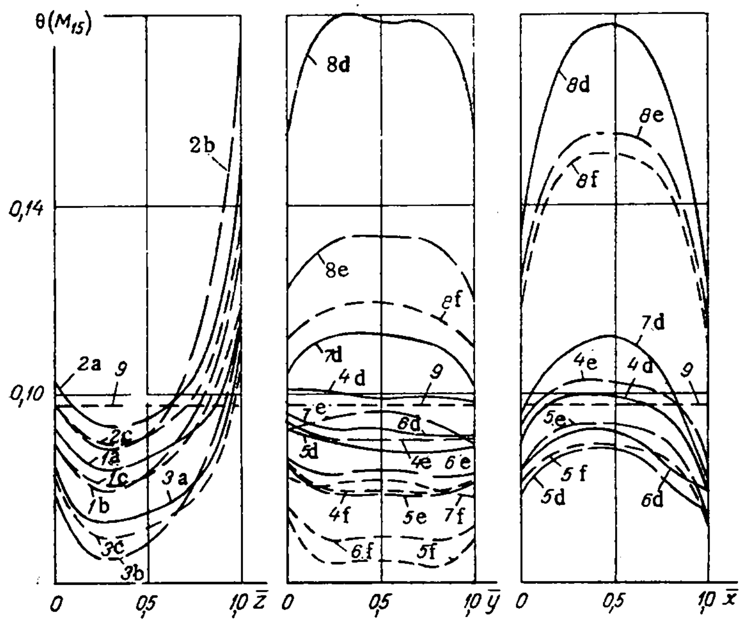

Fig. 4. Distribution of dimensionless temperature $\theta(M_{15})$ in volume V_{15} vs coordinate $\bar{x}$, $\bar{y}$, z: 1) x = 0; 2) x = 0.5a; 3) x = a; 4) z = 0; 5) z = 0.25 h_1; 6) z = 0.5 h_1; 7) z = 0.75 h_1; 8) z = h_1; 9) θ_{15}; a) y = 0; b) y = 0.5b; c) y = b; d) $\bar{x}(\bar{y})$ = 0.5; e) $\bar{x}(\bar{y})$ = 0; f) $\bar{x}(\bar{y})$ = 1 ($\bar{x}$ = x/a; $\bar{y}$ = y/b; $\bar{z}$ = z/h_1).

Figure 4 shows curves depicting the dependence of dimensionless temperature $\theta(M_{15})$ on coordinates x, y, z of points $M_{15} \in V_{15}$. These functions clearly show the complex character of the change in the temperature field of the medium in V_{15}. The functions have the same character only over height z of V_{15}. With removal from the upper boundary of the volume V_{15} the medium temperature first decreases, reaching minimum values at z ≈ 0.25 h_1, then increases, more significantly, the greater z. The greatest change in dimensionless temperature $\theta(M_{15})$ with coordinates x, y, occurs at z = h_1 = const. The figure also shows the mean value of the temperature θ_{15} of volume V_{15}.

NOTATION

$E_{\alpha i}$, $\tilde{R}_i$, generalized characteristics of boundary radiation of surface F_i; $\eta_{\alpha,i}$, $\varkappa_i$, generalized characteristics of volume radiation of volume V_i of medium; $E_{ef}(M_i)$, $E_{ef,i}$, local and mean surface densities of effective radiation of surface F_i at point $M_i \in F_i$; $\eta_{ef}(M_i)$, $\eta_{ef,i}$, local and mean densities of volume effective radiation at point $M_i \in V_i$: $E_{inc}(M_i)$, $E_{inc,i}$, local and mean densities of incident radiation at point M_i of surface F_i; $\eta_{inc}(M_i)$, $\eta_{inc,i}$, local and mean spatial densities of incident radiation at point M_i of volume V_i; $E_{res}(M_i)$, $E_{res,i}$, local and mean surface densities of resultant radiation at point $M_i \in F_i$; $\eta_{res}(M_i)$, $\eta_{res,i}$, local and mean densities of volume resultant radiation at point $M_i \in V_i$; $\alpha(M)$, coefficient of volume absorption at point M of medium; $\beta(M)$, coefficient of volume scattering at point M of medium; $k = \alpha + \beta$, extinction coefficient of medium; h(M, N), optical length of ray between points M and N; $\psi(M_i, F_k)$, local generalized angular coefficient of radiation from elementary area dF_{M_i}, located at point M_i of surface F_i onto surface F_k through intermediate attenuating medium; $\psi^{(1)}(M_i, F_k)$ generalized solid angle with apex at point M_i of volume V_i bounded by surface F_k; $A(M_i, V_j) = 4 k_j \rho(M_i, V_j)$, local attenuation of volume V_j of medium at point M_i of surface F_i (at k_j = const); $A^{(1)}(M_i, V_j) = 4 k_j \rho^{(1)}(M_i, V_j)$, addition to generalized solid angle with apex at point M_i of volume $V_i (M_i \in V_i)$; ψ_{ik}, mean generalized angular radiation coefficient from surface F_i onto surface F_k through intermediate absorbing and scattering medium; $A_{ij} = 4 k_j \rho_{ij}$ and $A_{sj}^{(1)} = 4 k_j \rho_{sj}^{(1)}$, mean attenuation of volume V_j of medium from surface F_i and volume V_s.

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