RADIATION OF TWO-PHASE MEDIA BOUNDED BY REFLECTING AND RADIATING SURFACES

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Regularities of radiation propagation in anisotropically dissipating media bounded by surfaces with given optical properties are investigated in the single-scattering approximation.

Investigation of the regularities of radiation propagation in two-phase media bounded by reflecting and radiating surfaces is of importance for the solution of radiant heat transfer properties in power plants where the heat carrier is ordinarily a gas—solid particle system, and in solving applied spectroscopy questions. At this time this problem plays a decisive part in the interpretation of experimental results obtained from on board long-range orbital stations and artificial earth satellites. A solution of the radiation transport equation in a two-phase layer is obtained below in the single-scattering approximation and takes into account the optical characteristics of the boundary surfaces in general form. The results are made specific for the diffusion and Fresnel (or specular) radiation reflection laws. The need to obtain the mentioned solution in general form is due also to the development of a method proposed in [1]. According to [1], the general solution of the radiation transport equation in a homogeneous anisotropic dissipating medium with arbitrary boundary conditions has the form

$$I(\tau,\ \mu) = I^{(0)}(\tau,\ \mu) + \Lambda(1+\Delta)I^{(1)}(\tau,\ \mu), \tag{1}$$

where $I^{(n)}(\tau,\ \mu)$ is the brightness of the n-tuply scattered radiation, and $\Delta = \Delta(\tau,\ \mu)$ is the correction for multiplicity of the scattering. As is shown in [1], the formula (1) permits the computation of the radiation characteristics of two-phase media with the scattering anisotropy, the optical properties of the boundary surfaces, etc., all taken into account.

Let us consider the radiation transport equation in a plane two-phase medium with amplitude dependence under the most general boundary conditions. Let a directional external power flux πI_0 be incident on the surface z = 0 of the medium (Fig. 1), and, moreover, a certain diffuse radiation I_{1g} as well. This might be radiation emitted by the surface z = 0 or penetrating the medium from outside. Diffuse radiation I_{2g} is incident from the boundary surface $z = z_0$. Analogously to [2], we introduce the quantity $y(\vec{l},\ \vec{l}')$ which is the probability that a light quantum incident on the surface of the medium in the direction $\vec{l}' = \vec{l}(\theta', \varphi')$ is reflected in the direction $\vec{l} = \vec{l}(\theta,\ \varphi)$ within the solid angle Ω. Then the brightness of the reflected radiation can be represented in the form [2]

$$\mu' I(\tau,\ \vec{l}') = (2\pi)^{-1} y(\vec{l}',\ \vec{l})\,\mu I(\tau,\ \vec{l}). \tag{2}$$

If the surface reflects isotropically, then

$$y = 2q\mu, \tag{3}$$

where q is the albedo of the surface. The Fresnel (or specular) reflection of the radiation from the surface is described by the function

$$y(\vec{l},\ \vec{l}') = 2\pi r(\mu)\,\delta(\vec{l} - \vec{l}'), \tag{4}$$

where δ is the Dirac function.

The radiation transport equation in a plane medium has the form [2]

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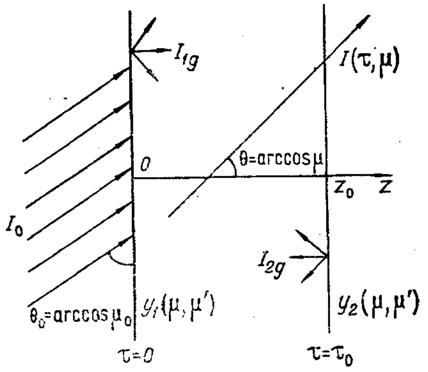

Fig. 1. On formulation of the problem.

$$\mu\frac{\partial I(\tau,\vec{l})}{\partial\tau}+I(\tau,\vec{l})=\Lambda(4\pi)^{-1}\int\limits_{(4\pi)}p(\vec{l},\vec{l}')I(\tau,\vec{l}')d\vec{l}'+(1-\lambda)S(\tau). \tag{5}$$

Here $\mu\in[-1, 1]$; $\varphi\in[0, 2\pi]$; $d\vec{l}'=d\mu'd\varphi'$; $S(\tau)$ is a function of the internal sources which in the case of local thermodynamic equilibrium agrees with the Planck function. The boundary conditions for the problem formulated are (see Fig. 1)

$$I(0,\vec{l})=\pi I_0\delta(\vec{l}-\vec{l}_0)+I_{1g}+(2\pi\mu)^{-1}\int\limits_{(2\pi)}\mu'y_1(\vec{l},\vec{l}')I(0,-\vec{l}')d\vec{l}',$$
$$I(\tau_0,-\vec{l})=I_{2g}+(2\pi\mu)^{-1}\int\limits_{(2\pi)}\mu'y_2(\vec{l},\vec{l}')I(\tau_0,\vec{l}')d\vec{l}', \tag{6}$$

where $-\vec{l}=\vec{l}(-\mu,\varphi)$.

The solution of (5) in the single-scattering approximation reduces to solving the equations

$$\mu\frac{\partial I^{(0)}(\tau,\vec{l})}{\partial\tau}+I^{(0)}(\tau,\vec{l})=S(\tau), \tag{7}$$

$$\mu\frac{\partial I^{(1)}(\tau,\vec{l})}{\partial\tau}+I^{(1)}(\tau,\vec{l})=(4\pi)^{-1}\int\limits_{(4\pi)}p(\vec{l},\vec{l}')I^{(0)}(\tau,\vec{l}')d\vec{l}'-S(\tau) \tag{8}$$

with the boundary conditions

$$I^{(0)}(0,\vec{l})=\pi I_0\delta(\vec{l}-\vec{l}_0)+I_{1g}+(2\pi\mu)^{-1}\int\limits_{(2\pi)}y_1(\vec{l},\vec{l}')I^{(0)}(0,-\vec{l}')\mu'dl', \tag{9}$$
$$I^{(0)}(\tau_0,-\vec{l})=I_{2g}+(2\pi\mu)^{-1}\int\limits_{(2\pi)}y_2(\vec{l},\vec{l}')I^{(0)}(\tau_0,\vec{l}')\mu'dl',$$

$$I^{(1)}(0,\vec{l})=(2\pi\mu)^{-1}\int\limits_{(2\pi)}y_1(\vec{l},\vec{l}')I^{(1)}(0,-\vec{l}')\mu'd\vec{l}', \tag{10}$$
$$I^{(1)}(\tau_0,-\vec{l})=(2\pi\mu)^{-1}\int\limits_{(2\pi)}y_2(\vec{l},\vec{l}')I^{(1)}(\tau_0,\vec{l}')\mu'd\vec{l}'.$$

The solution of problem (7) and (9) can be represented in the form

$$I^{(0)}(\tau,\vec{l})=Q_1(\tau,\vec{l})+\pi I_0\delta(\vec{l}-\vec{l}_0)\exp(-\tau/\mu), \tag{11}$$
$$I^{(0)}(\tau,-\vec{l})=Q_2(\tau,\vec{l}),$$

where

$$Q_1(\tau,\vec{l})=\varepsilon_1(\tau,\mu)+\left[I_{1g}+(2\pi\mu)^{-1}\int\limits_{(2\pi)}y_1(\vec{l},\vec{l}')I^{(0)}(0,-\vec{l}')\mu'd\vec{l}'\right]\exp(-\tau/\mu); \tag{12}$$

$$Q_2(\tau, \vec{l}) = \varepsilon_2(\tau, \mu) + \left[I_{2g} + (2\pi\mu)^{-1} \int_{(2\pi)} y_2(\vec{l}, \vec{l}') I^{(0)}(\tau_0, \vec{l}') \mu' d\vec{l}'\right] \exp[-(\tau_0 - \tau)/\mu];$$

$$\varepsilon_1(\tau, \mu) = \int_0^\tau S(\tau') \exp[-(\tau - \tau')/\mu] \frac{d\tau'}{\mu},$$

$$\varepsilon_2(\tau, \mu) = \int_\tau^{\tau_0} S(\tau') \exp[-(\tau' - \tau)/\mu] \frac{d\tau'}{\mu}.$$

It is hence easy to find a system of integral equations to determine the quantities $I^{(0)}(0, -\vec{l})$ and $I^{(0)}(\tau_0, \vec{l})$, i.e., the characteristics of the radiation emerging from the layer. This system is radically simplified for particular laws of radiation reflection from the boundary surfaces. Thus, in the case of the Lambert reflection law for both surfaces, the relations (11) go over into the following:

$$I^{(0)}(\tau, \vec{l}) = \varepsilon_1(\tau, \mu) + [\pi I_0 \delta(\vec{l} - \vec{l}_0) + I_{1g} + \pi^{-1} q_1 H_2^{(0)}(0)] \exp(-\tau/\mu), \tag{13}$$

$$I^{(0)}(\tau, -\vec{l}) = \varepsilon_2(\tau, \mu) + [I_{2g} + \pi^{-1} q_2 H_1^{(0)}(\tau_0)] \exp[-(\tau_0 - \tau)/\mu].$$

Here the functions

$$H_1^{(0)}(\tau) = \int_{(2\pi)} I^{(0)}(\tau, \vec{l}) \mu d\vec{l} \quad \text{and} \quad H_2^{(0)}(\tau) = \int_{(2\pi)} I^{(0)}(\tau, -\vec{l}) \mu d\vec{l} \tag{14}$$

are none other than the magnitudes of the radiation fluxes towards the lower and upper boundary surfaces, respectively. According to (11)

$$H_1^{(0)}(\tau_0) = h_0 \{\varepsilon_1^0 + \pi I_0 \mu_0 V_0 + 2E_3(\tau_0)[\pi I_{1g} + q_1 \varepsilon_2^0 + 2\pi q_1 I_{2g} E_3(\tau_0)]\}, \tag{15}$$

$$H_2^{(0)}(0) = h_0 \{\varepsilon_2^0 + 2E_3(\tau_0)[\pi I_{2g} + q_2 \varepsilon_1^0 + 2\pi q_2 I_{1g} E_3(\tau_0) + \pi q_2 I_0 \mu_0 V_0]\}, \tag{16}$$

$$V_0 = \exp(-\tau_0/\mu_0), \quad h_0 = [1 - 4 q_1 q_2 E_3^2(\tau_0)]^{-1},$$

$$\varepsilon_1^0 = 2\pi \int_0^1 \varepsilon_1(\tau_0, \mu) \mu d\mu = 2\pi \int_0^{\tau_0} E_2(\tau_0 - \tau') S(\tau') d\tau', \tag{17}$$

$$\varepsilon_2^0 = 2\pi \int_0^{\tau_0} E_2(\tau') S(\tau') d\tau',$$

$E_n(x) = \int_0^1 e^{-sx} s^{-n} ds$ is the exponential integral function. The quantities ε_i^0 (i = 1, 2) are the brightness of the intrinsic layer radiation averaged over the hemispheres.

If both surfaces reflect by the Fresnel law as occurs in practice when studying the spectroscopic characteristics of media in cuvettes, then

$$I^{(0)}(\tau, \vec{l}) = \varepsilon_1(\tau, \mu) + [\pi I_0 \delta(\vec{l} - \vec{l}_0) + I_{1g} + r_1(\mu) B_1(\mu)] \exp(-\tau/\mu), \tag{18}$$

$$I^{(0)}(\tau, -\vec{l}) = \varepsilon_2(\tau, \mu) + [I_{2g} + r_2(\mu) B_2(\mu)] \exp[-(\tau_0 - \tau)/\mu],$$

where

$$B_1(\mu) = b_0 \{\varepsilon_2(0, \mu) + I_{2g} V_1 + r_2(\mu) V_1 [\varepsilon_1(\tau_0, \mu) + \pi I_0 \delta(\vec{l} - \vec{l}_0) V_1 + I_{1g} V_1]\}; \tag{19}$$

$$B_2(\mu) = b_0 \{\varepsilon_1(\tau_0, \mu) + V_1 [\pi I_0 \delta(\vec{l} - \vec{l}_0) + I_{1g} + r_1(\mu) \varepsilon_2(0, \mu) + r_1(\mu) I_{2g} V_1]\};$$

$$b_0 = [1 - r_1(\mu) r_2(\mu) \exp(-2\tau_0/\mu)]^{-1}; \quad V_1 = \exp(-\tau_0/\mu). \tag{20}$$

If one of the boundary surfaces (the lower, say) reflects by the Lambert law, while the second is specular, then the light field in the two-phase medium will be determined by the relationships

$$I^{(0)}(\tau, \vec{l}) = \varepsilon_1(\tau, \mu) + \{\pi I_0 \delta(\vec{l} - \vec{l}_0) + I_{1g} + \varepsilon_2(0, \mu) r_1(\mu) + [r_1(\mu) I_{2g} + \pi^{-1} r_1(\mu) q_2 H_{1r}^{(0)}(\tau_0)] V_1\} \exp(-\tau/\mu), \tag{21}$$

$$I^{(0)}(\tau, -\vec{l}) = \varepsilon_2(\tau, \mu) + [I_{2g} + \pi^{-1} q_2 H_{1r}^{(0)}(\tau_0)] \exp[-(\tau_0 - \tau)/\mu],$$

where

$$H_{1r}^{(0)}(\tau_0) = [1 - 2q_2 D_1(2\tau_0)]^{-1} \{\varepsilon_1^0 + \varepsilon_{2r}^0 + \pi I_0 \mu_0 V_0 + 2\pi [I_{1g} E_3(\tau_0) + I_{2g} D_1(2\tau_0)]\}, \tag{22}$$

$$\varepsilon_{2r}^0 = 2\pi \int_0^1 r_1(\mu) \varepsilon_2(0, \mu) e^{-\frac{\tau_0}{\mu}} \mu d\mu; \; D_1(x) = \int_0^1 r_1(\mu) e^{-\frac{x}{\mu}} \mu d\mu. \tag{23}$$

The expressions (13), (18), and (21) obtained are of independent interest since they permit the study of a light field within a medium and the characteristics of the emerging radiation as a function of the optical properties of the medium and of the boundary surfaces in the absence of scattering processes.

Substituting (11) into the integral term of (8), we obtain an equation to determine the brightness of the radiation with single scattering processes taken into account. Under the boundary conditions (10) it is easy to find the solution of this equation

$$I^{(1)}(\tau, \vec{l}) = K_1(\tau, \vec{l}) - \varepsilon_1(\tau, \mu) + I_0 \mu_0 \frac{p(\vec{l}, \vec{l}_0)}{4(\mu_0 - \mu)} (e^{-\frac{\tau}{\mu_0}} - e^{-\frac{\tau}{\mu}}) + (2\pi\mu)^{-1} e^{-\frac{\tau}{\mu}} \int_{(2\pi)} y_1(\vec{l}, \vec{l}') I^{(1)}(0, -\vec{l}') \mu' d\vec{l}', \tag{24}$$

$$I^{(1)}(\tau, -\vec{l}) = K_2(\tau, \vec{l}) - \varepsilon_2(\tau, \mu) + I_0 \mu_0 \frac{p(-\vec{l}, \vec{l}_0)}{4(\mu_0 + \mu)} [e^{-\frac{\tau}{\mu_0}} - e^{-\frac{\tau_0 - \tau}{\mu}} V_0] + (2\pi\mu)^{-1} e^{-\frac{\tau_0 - \tau}{\mu}} \int_{(2\pi)} y_2(\vec{l}, \vec{l}') I^{(1)}(\tau_0, \vec{l}') \mu' d\vec{l}'. \tag{25}$$

Here

$$K_1(\tau, \vec{l}) = \int_0^\tau L(\tau', \vec{l}) \exp[-(\tau - \tau')/\mu] \frac{d\tau'}{\mu};$$

$$K_2(\tau, \vec{l}) = \int_\tau^{\tau_0} L(\tau', \vec{l}) \exp[-(\tau' - \tau)/\mu] \frac{d\tau'}{\mu}; \tag{26}$$

$$L(\tau, \vec{l}) = (4\pi)^{-1} \int_{(2\pi)} [p(\vec{l}, \vec{l}') Q_1(\tau, \vec{l}') + p(\vec{l}, -\vec{l}') Q_2(\tau, \vec{l}')] d\vec{l}'.$$

To determine the quantities $I^{(1)}(\tau_0, \vec{l})$ and $I^{(1)}(0, -\vec{l})$ in (24) and (25), we obtain the following integral equations

$$I^{(1)}(\tau_0, \vec{l}) = i_1(\vec{l}) + (4\pi^2\mu^2)^{-1} V_1 \int_{(2\pi)} y_1(\vec{l}, \vec{l}') V_1 \mu' d\vec{l}' \int_{(2\pi)} y_2(\vec{l}', \vec{l}'') I^{(1)}(\tau_0, \vec{l}'') \mu'' d\vec{l}'', \tag{27}$$

$$I^{(1)}(0, -\vec{l}) = i_2(\vec{l}) + (4\pi^2\mu^2)^{-1} V_1 \int_{(2\pi)} y_2(\vec{l}, \vec{l}') V_1 \mu' d\vec{l}' \int_{(2\pi)} y_1(\vec{l}', \vec{l}'') I^{(1)}(0, -\vec{l}'') \mu'' dl'', \tag{28}$$

where

$$i_1(\vec{l}) = K_1(\tau_0, \vec{l}) - \varepsilon_1(\tau_0, \mu) + I_0 \mu_0 \sigma^{(1)}(\vec{l}, \vec{l}_0) + (2\pi\mu)^{-1} V_1 \int_{(2\pi)} y_1(\vec{l}, \vec{l}') [K_2(0, \vec{l}') - \varepsilon_2(0, \mu') + I_0 \mu_0 \rho^{(1)}(-\vec{l}', \vec{l}_0)] \mu' d\vec{l}'; \tag{29}$$

$$i_2(\vec{l}) = K_2(0, \vec{l}) - \varepsilon_2(0, \mu) + I_0 \mu_0 \rho^{(1)}(-\vec{l}, \vec{l}_0) + (2\pi\mu)^{-1} V_1 \int_{(2\pi)} y_2(\vec{l}, \vec{l}') [K_1(\tau_0, \vec{l}') - \varepsilon_1(\tau_0, \mu') + I_0 \mu_0 \sigma^{(1)}(\vec{l}', \vec{l}_0)] \mu' d\vec{l}'; \tag{30}$$

$$\sigma^{(1)}(\vec{l}, \vec{l}_0) = \frac{p(\vec{l}, \vec{l}_0)}{4(\mu_0 - \mu)} (V_0 - V_1); \; \rho^{(1)}(-\vec{l}, \vec{l}_0) = \frac{p(-\vec{l}, \vec{l}_0)}{4(\mu_0 + \mu)} (1 - V_0 V_1),$$

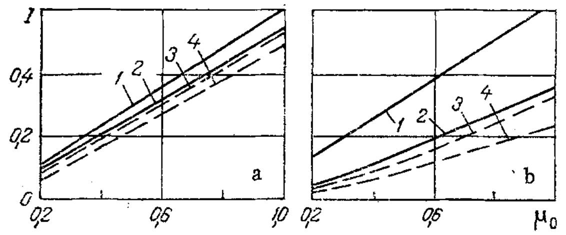

Fig. 2. Dependence of the brightness of radiation emerging from the atmosphere on the zenith angle of the sun for $\tau_0 = 0.1$ (a) and $\tau_0 = 0.5$ (b): 1) computation taking into account multiple scattering according to [7]; 2, 3, 4) computation in the single-scattering approximation using (31), (33), and (34), respectively.

and $\sigma^{(1)}(\vec{l}, \vec{l}_0)$ and $\rho^{(1)}(-\vec{l}, \vec{l}_0)$ are the transmission and brightness factors of the layer in the single scattering approximation.

The solution of (24) and (25) in combination with (27) and (28) describes the light field in a radiating two-phase medium bounded by surfaces with previously assigned optical properties in the most general form with single-scattering taken into account. It substantially includes all possible practical situations. The relations obtained are extremely simplified upon assignment of specific radiation reflection laws by the boundary surfaces, upon investigation of isothermal two-phase media, etc. Thus for instance, if both boundary surfaces reflect radiation by the Fresnel law, then the radiation emerging from the medium is described by the relations

$$I^{(1)}(\tau_0, \vec{l}) = R[F_1 + r_1(\mu)V_1F_2], \quad I^{(1)}(0, -\vec{l}) = R[F_2 + r_2(\mu)V_1F_1],$$
$$F_1 = K_1(\tau_0, \vec{l}) - \varepsilon_1(\tau_0, \mu) + I_0\mu_0\sigma^{(1)}(\vec{l}, \vec{l}_0),$$
$$F_2 = K_2(0, \vec{l}) - \varepsilon_2(0, \mu) + I_0\mu_0\rho^{(1)}(-\vec{l}, \vec{l}_0),$$
$$R = [1 - r_1(\mu)r_2(\mu)\exp(-2\tau_0/\mu)]^{-1}.$$

In conclusion, let us consider the problem of diffuse reflection of radiation by a two-phase medium with an underlying surface. We note that its solution plays an important role in the interpretation of remote measurements. We assume that $I_{1g} = I_{2g} = 0$, and we also neglect the intrinsic radiation of the atmosphere, as is valid for the visible spectrum range. Then we can write for the radiation brightness on the upper boundary of the atmosphere in the single-scattering approximation

$$I(0, -\vec{l}) = I^{(0)}(0, -\vec{l}) + \Lambda I^{(1)}(0, -\vec{l}) = I_0\mu_0[qV_0V_1 + \Lambda\rho^{(1)}(-\vec{l}, \vec{l}_0) + \Lambda qV_0\bar{V}(-\vec{l}) + \Lambda qV_1\bar{V}(\vec{l}_0) + \Lambda q^2V_0V_1A_s], \quad (31)$$

where

$$\bar{V}(\vec{l}) = \pi^{-1}\int_{(2\pi)}\sigma^{(1)}(\vec{l}', \vec{l})\,d\vec{l}';$$
$$A_s = \pi^{-2}\int_{(2\pi)}d\vec{l}_0\int_{(2\pi)}\rho^{(1)}(-\vec{l}', \vec{l}_0)\,d\vec{l}'. \quad (32)$$

Here V_0 and $\bar{V}(\vec{l}_0)$ are transmission functions of the atmosphere for unscattered and single scattered radiation while A_s is the spherical albedo of the atmosphere [2].

To simplify the calculations, we take the average of (31) with respect to the aximuthal angle φ and we use the condition of total diffusivity of the radiation [3, 4]. It is that the brightness of the diffuse radiation emerging from the layer and averaged over the directions will equal the brightness of the radiation emerging from the layer at the angle $\theta = 60°$ ($\mu = 1/2$). Then

$$I(0,\ -\vec{l})=I_0\mu_0\Big\{\Lambda\rho^{(1)}(-\vec{l},\ \vec{l}_0)+qV_0V_1\Big[1+\frac{\Lambda p\left(\mu,\ \frac{1}{2}\right)}{2(2\mu-1)}\left(1-\exp\left(-\frac{2\mu-1}{\mu}\tau_0\right)\right)+$$

$$+\frac{\Lambda p\left(\frac{1}{2},\ \mu_0\right)}{2(2\mu_0-1)}\left(1-\exp\left(-\frac{2\mu_0-1}{\mu_0}\tau_0\right)\right)+\frac{\Lambda}{4}qp\left(-\frac{1}{2},\ \frac{1}{2}\right)(1-e^{-4\tau_0})\Big]\Big\}. \quad (33)$$

The angular dependence of the radiation at the upper boundary of the atmosphere is represented in Fig. 2 for the albedo $q = 0.6$; $\Lambda = 1$; $I_0 = 1$, $\tau_0 = 0.1$ (a) and $\tau_0 = 0.5$ (b). Used as scattering index is the anisotropic index of the Astrophysical Institute of the Kazakh Academy of Sciences for the wave length 0.55 μm [5]. The results were analyzed in the azimuthal plane $\varphi=\varphi_0=0°$ and for a sighting angle of $\theta = 180°$ ($|\mu| = 1$). Singly scattered radiation was evaluated by means of (31) and (33) as well as by the simplified expression ordinarily utilized in practice [6]

$$I_{\text{упр}}(0,\ -\vec{l})=I_0\mu_0[\Lambda\rho^{(1)}(-\vec{l},\ \vec{l}_0)+qV_0V_1]. \quad (34)$$

Presented in the figure are the results of numerical solution of the transport equation by the method of characteristics [7]. Comparison of the computation data presented in Fig. 2 shows that utilization of (34) in place of (31) increases the error in the computation by 1.5-2.5 times. Let us note that as μ diminishes, i.e., as the angle of observation increases, and the optical thickness grows, the error in the computations in the single-scattering approximation increases. Thus if for $\tau_0 = 0.5$ and $\mu = 1.0$ $\Delta \sim 7\%$, then for $\mu \sim 0.2$ it reaches 50%. The influence of these factors on the increase in the error is completely evident since as μ diminishes and τ_0 increases the role of multiple scattering grows, and to achieve previously assigned accuracy it is necessary to involve (1) for the computations. It should be emphasized that the relations (31) and (33) differ insignificantly from each other even for a strongly extended scattering index. Hence, for simplicity and graphical computations in practice, the principal of complete diffusivity of the radiation can be used [3, 4]. Its validity in the example of a spherical, Rayleigh, and linear scattering index is shown also in [8] for the problem of radiation propagation in a medium with underlying surface without taking account of the azimuthal dependence of the radiation brightness.

NOTATION

$I(\tau,\ \vec{l})$, radiation brightness at the point τ and direction $\vec{l}(\theta,\ \varphi)$ determined by the angles $\theta = \arccos\mu$ and φ; $p(\vec{l},\ \vec{l}')$, radiation scattering index per volume element of the medium; $S(\tau)$, a function of the internal radiation sources; $y(\vec{l},\ \vec{l}')$, directional reflexivity of the boundary surface; $r(\mu)$, Fresnel reflection coefficient; $\varkappa$ and σ, absorption and scattering indices; $\Lambda=\sigma/(\varkappa+\sigma)$, probability of survival of a quantum; $\tau=\int_0^z(\varkappa+\sigma)\,dz$, optical thickness; $\tau_0=\int_0^{z_0}(\varkappa+\sigma)\,dz$, total optical thickness of the layer; and q, albedo.

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TEMPERATURE MEASUREMENTS ON AN AIR PLASMA JET IN AN INDUCTION PLASMATRON AT REDUCED PRESSURES

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Temperature measurements are reported for a subsonic free air-plasma jet derived from a VGU-2 plasmatron in the pressure range $5 \cdot 10^3 \leqslant P \leqslant 10^5$ Pa.

There are a few papers in which temperatures in air induction plasmas have been measured by spectral methods; they relate to discharges with air blown through them [1-5] or without throughflow [6] and relate in the main to the energy deposition zone. Although there were substantial differences between the equipments and various spectral methods were employed, it has been found that the state of an air plasma at atmospheric pressure is close to an equilibrium one. This conclusion cannot be transferred to the case where the induction plasma is produced in an air flow at pressures below atmospheric until additional studies have been made. This can then form the basis for temperature measurements in subsonic air jets at pressures of $5 \cdot 10^3$-10^5 Pa.

We consider the first negative system of N_2^+ ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ vibronic transition), which is observed in a spectral range convenient for measurement (3600-5200 Å), and which is reasonably strong and whose bands are present throughout the pressure range. We examined the relative intensity distribution of the lines in the rotational structure of N_2^+ in order to determine the gas temperature. We then derived the dependence of the jet temperature on pressure and the temperature distribution along the axis.

We examined the subsonic plasma jet obtained in a high-temperature gasdynamic apparatus type VGU-2. Jet parameters: power N = 31.6 kW, working gas air, pressure range $P = 5 \cdot 10^3$-10^5 Pa, flow speed V = 30-150 m/sec, and jet diameter D = 25-40 mm. The power was checked on the plate circuit of the vacuum-tube generator and was kept constant at 31.6 kW at all pressures.

Two complimentary methods were used: photographic (recording, spectrum identification, and absolute intensity measurement) and photoelectric (absolute intensity measurement).

In the photographic recording, the plasma column was imaged on the entrance slit of a DFS-13 grating spectrograph by means of an Industar-37 achromatic objective (the focal length 300 mm), the spectrograph having a dispersion of 2 Å/mm and a slitwidth of 50 μm. The image scale was 1:1. The photoelectric recording was made with a grating monochromator and spectrograph by the firm of McPherson (aperture 1:8.3, dispersion 8 Å/mm, slitwidth varied from 15 to 80 μm). The image in the entrance slit plane was formed with a scale of 1:2 or 1:1. The detector was an EMl photomultiplier behind the exit slit. The photomultiplier signal passed via an amplifier to a Rikadenki two-pen recorder.

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