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RADIATION ATTENUATION BY DISPERSE MEDIA

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Abstract—The volumetric coefficients of attenuation and scattering, and scattering indicatrices of disperse media with metallic additives are analyzed. The methods to calculate radiant fluxes in anisotropically scattering media are proposed for parallelplane and spherically symmetric beds. The effect of the parameters of a medium microstructure on radiant fluxes is studied.

NOMENCLATURE

- a_i, coefficients of expansion into Legendre polynomial series of the scattering indicatrix;
- d, specific weight of particle material;
- I_λ, monochromatic radiation intensity;
- $I_{B\lambda}$, monochromatic radiation intensity of absolutely black body;
- $i_1(\theta), i_2(\theta)$, Mie-functions [1];
- k_λ, attenuation coefficient;
- k_{att}, k_{scat}, coefficients of attenuation and scattering on a single particle;
- L, bed thickness;
- $P_i(\mu)$-, ith Legendre polynomial;
- q_R, radiant flux;
- r_0, modal radius;
- T, temperature;
- α_λ, absorption coefficient;
- β_λ, scattering coefficient;
- $P(\mu,\mu')$, $= \sum_{i=0}^{I} a_i P_i(\mu) P_i(\mu')$;
- γ, weight particle concentration;
- δ_{0k}, Kronecker symbol;
- ε_i, emissivity;
- Θ, dimensionless temperature;
- Θ, angle;
- λ, wavelength;
- μ, $= \cos\theta$;
- μ_0, parameter of medium microstructure;
- ξ, geometry factor;
- ρ, difraction parameter;
- ω_λ, ω_0, spectral and integral albedo of single scattering.

OPAQUE particles capable of absorbing and scattering radiation may usefully be introduced into the wall layer in many problems on surface protection from thermal radiation. The problems on hydrodynamics and radiative transfer in a non-uniform gas flow are characterized by great complexity, and particular aspects are studied inadequately, because alongside with radiative-convective transfer phase transitions, coagulation and aglomeration of particles should be accounted for. First of all, study of optical properties of a unit volume of a disperse medium seems probably useful since calculation of radiant fluxes in disperse media is based on the data on attenuation coefficients and scattering indicatrices of a unit volume.

In this work radiant attenuation due to absorption and scattering by a unit volume of a polydisperse medium with metallic additives is investigated within the framework of the single scattering theory. Multiple scattering occurs when radiation passes through a disperse bed. The method to calculate radiant fluxes in a parallel-plane and spherically symmetric disperse bed is proposed. The effect of scattering parameters and medium microstructure on radiant fluxes is analyzed.

1. REGULARITIES OF RADIANT ATTENUATION AND SCATTERING BY MONO- AND POLYDISPERSE MEDIA

Radiation attenuation by single spherical particles due to absorption and scattering is thoroughly studied using Mie's theory [1]. Most detailed studies are described in [2–5]. For example, a particle cluster in the systems of different-size particles is of practical interest for studying thermal protective materials. At present vast material on radiation attenuation and scattering by such polydisperse media has been accumulated. The results obtained in [5–7] have essentially contributed to the information on radiant scattering, but they contain either parametric calculations or the analysis of scattering phenomena by specific media: aqueous aerosols, hail, dust clouds, etc. These works are therefore of little interest for studying radiative attenuation by disperse media with metallic particles.

The calculation which will follow allow the relationships between basic values of radiant absorption and scattering and the microstructure of a disperse medium with metallic spherical particles to be thoroughly elucidated. The data on the complex refraction index typical for many metals and used for calculating attenuation coefficients and indicatrices are given in Fig. 1.

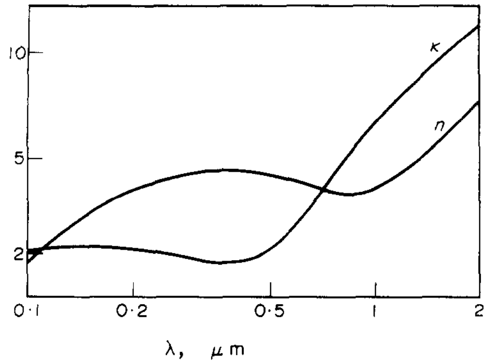

FIG. 1. Complex index of refraction $m = n - i\kappa$ vs wavelength.

1.1. *Monodisperse bed*

A monodisperse bed is the extreme case of a polydisperse one. The values of the attenuation coefficients of a monodisperse bed allow the upper limit of the same coefficients of a polydisperse bed to be found.

If a unit volume of a transparent gas contains N non-reacting particles of uniform radius r with the distance between their centres at least $3r$, then the volumetric attenuation coefficient is defined by [3]:

$$k_\lambda = N\pi r^2 k_{att}, \tag{1}$$

where k_{att} is the attenuation coefficient for a single particle. In many practical problems, it is more convenient to prescribe the dependence in the unit volume on the weight concentration rather than on the particle quantity in a unit volume γ:

$$k_\lambda = \frac{3\pi}{2\lambda}\frac{\gamma}{d}\frac{k_{att}}{\rho}, \tag{1''}$$

where d is the specific weight of the particle material.

The formulae for volumetric coefficients of scattering and absorption are the same. Figure 2 gives the plot of spectral mass coefficients of attenuation k_λ/γ and scattering β_λ/γ vs particle radius r. The quantities k_{att}, k_{scat} in formula (1″) are calculated for single particles using Mie's formula [1] based on Deirmendjan's methods [5]. The curves in Fig. 2 show that particles 0·01–0·03 μm in radius possess the largest attenuation coefficients but only over a narrow range of the wavelengths considered. Particles 0·05–0·07 μm in radius are therefore more effective for radiant attentuation, since these have large attenuation coefficients and a smooth spectral relationship over a sufficiently wide spectral range.

1.2. *Polydisperse bed*

Now consider a polydisperse medium assuming that all particles are spherical and possess the same optical properties. The microstructure of the polydisperse medium is characterized by the particle size distribution function $f(r)$. In many cases a sufficient approximation to the real distribution is ensured by the gamma-distribution (Fig. 3):

$$f(r) = Ar^{\mu_0}\exp\left[-\mu_0\frac{r}{r_0}\right] \tag{2}$$

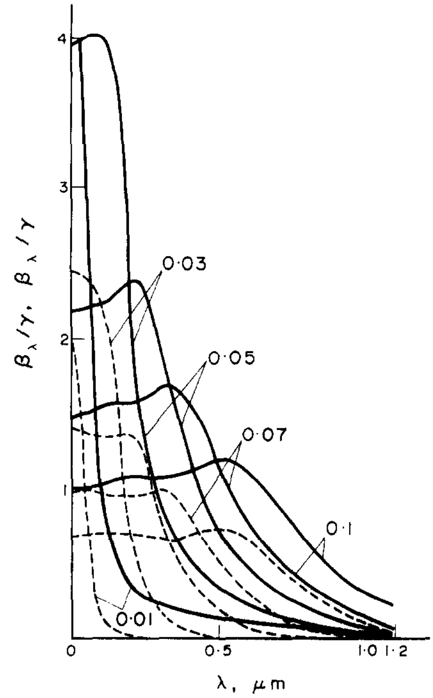

FIG. 2. Spectral mass coefficients of attenuation (solid lines) and scattering (dashed lines) of monodisperse media vs particle radius.

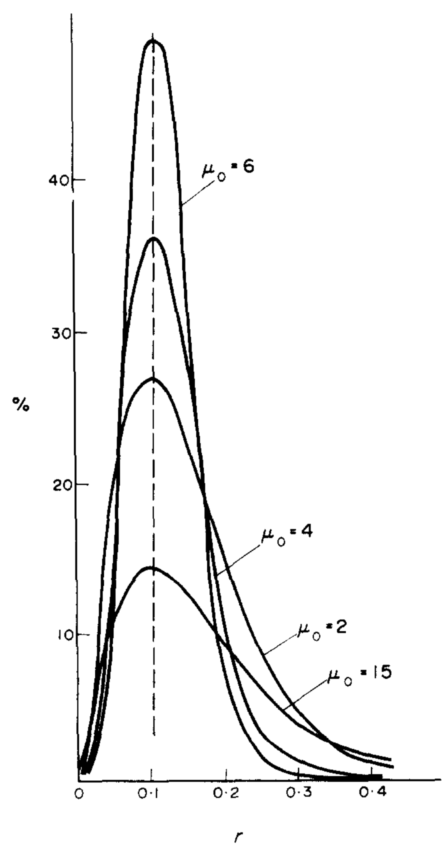

FIG. 3. Particle size gamma-distribution at $r_0 = 0{\cdot}1$ μm.

where A is the normalization factor, μ_0 is the parameter of the relative half-width of the distribution function, r_0 is the most probable or modal particle radius. The half-width of function (2) or the distance between its branches B at the level $f(r) = 0{\cdot}5 . f(r_0)$ [13] is equal to:

$$B = 2{\cdot}48 r_0/\sqrt{(\mu_0)}.$$

The spectral volumetric attenuation coefficient k_λ for scattering β_λ and absorption α_λ in the polydisperse medium is described by:

$$k_\lambda = \frac{3}{4}\frac{\gamma}{d}\frac{2\pi}{\lambda}\frac{\int_{\rho_1}^{\rho_2} \rho^2 f(\rho) k_{\mathrm{att}}(\rho)\,\mathrm{d}\rho}{\int_{\rho_1}^{\rho_2} \rho^3 f(\rho)\,\mathrm{d}\rho} = \frac{3}{4}\frac{\gamma}{d} k'_\lambda. \quad (3)$$

The coefficients k'_λ, β'_λ and normalized indicatrices of scattering by a unit volume of the polydisperse medium

$$\Gamma(\theta) = \left(\frac{\lambda}{\pi}\right)^2 \frac{1}{8\pi\beta'_\lambda} \frac{\int_{r_1}^{r_2} [i_1(\theta)+i_2(\theta)] f(r)\,\mathrm{d}r}{\int_{r_1}^{r_2} r^3 f(r)\,\mathrm{d}r} \quad (4)$$

are calculated on the electronic computer Minsk-32 by the methods described in [7]. The modal particle radius r_0 varied within $0{\cdot}03 \leqslant r_0 \leqslant 1{\cdot}2\,\mu\mathrm{m}$; the parameter μ_0, within $2 \leqslant \mu_0 \leqslant 10$. Integration with respect to the sizes was made from $\rho_1 = 0{\cdot}025$ to ρ_2, determined by $f(\rho_2) = 10^{-5} f(\rho_0)$.

The spectral coefficients of attenuation k'_λ and scattering β'_λ (Figs. 4–6) are rather smooth functions of the wavelength at $r > 0{\cdot}1\,\mu\mathrm{m}$ (Fig. 4). Such polydisperse media may be considered grey over the wavelength range investigated. As far as the modal size r_0 decreases, the curves become non-linear (Fig. 5) and involve maxima most pronounced at $r_0 \leqslant 0{\cdot}05\,\mu\mathrm{m}$.

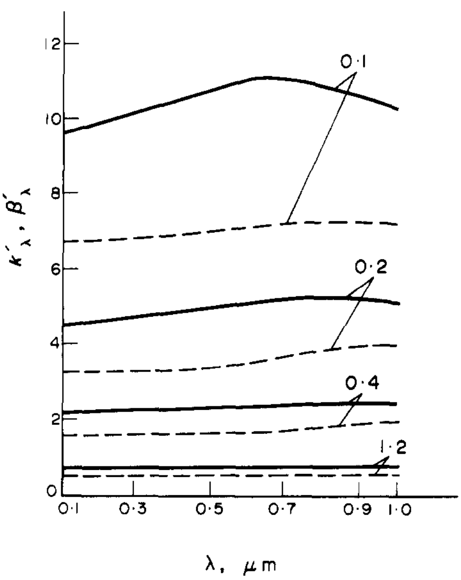

FIG. 4. Spectral coefficients of attenuation k'_λ (solid lines) and scattering β'_λ (dashed lines) versus modal particle size r_0 (figures at the curves at $\mu_0 = 2$.

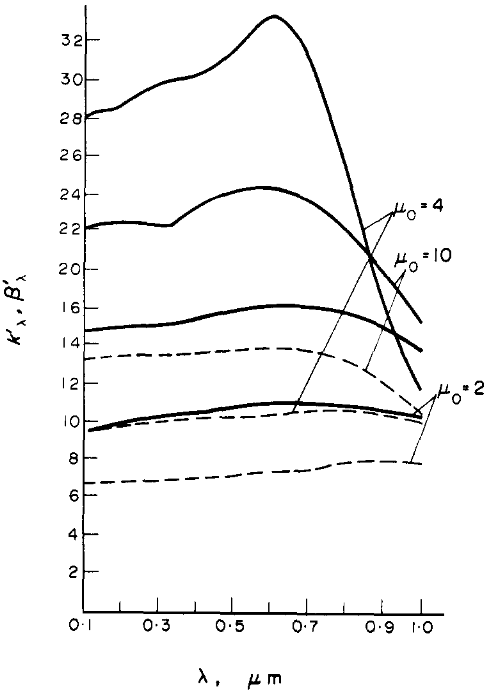

FIG. 5. Spectral coefficients of attenuation k'_λ (solid lines) and scattering β'_λ (dashed lines) vs parameter μ_0 for polydisperse medium, $r_0 = 0{\cdot}1\,\mu\mathrm{m}$. The upper curve—$k'_\lambda$ for monodisperse medium.

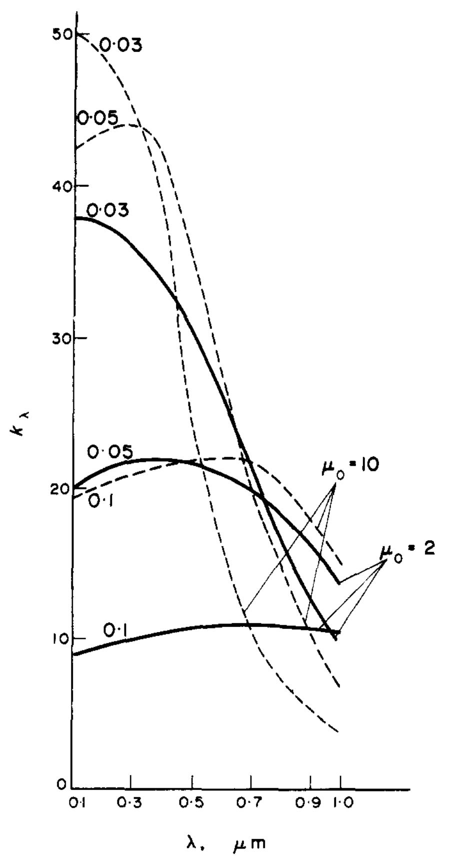

FIG. 6. Spectral attenuation coefficients k'_λ for fine polydispersions at $r_0 = 0{\cdot}05\,\mu\mathrm{m}$, $r_0 = 0{\cdot}03\,\mu\mathrm{m}$.

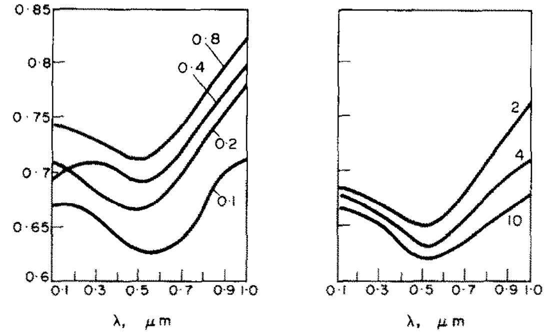

FIG. 7. Spectral distributions of parameter ω_λ for different modal radii at $\mu_0 = 6$ (a) and of parameter μ_0 (b) at $r_0 = 0{\cdot}1$ μm.

With an increase in μ_0 (Fig. 6), i.e. when the medium becomes monodisperse, the attenuation coefficients grow achieving the values for a monodisperse medium at $r = r_0$.

Figure 7(a, b) shows the effect of parameters r_0 and μ_0 upon the single scattering albedo ω_λ.

Typical scattering indicatrices for a unit volume of a polydisperse medium are given in Fig. 8.

For polydisperse media with fine particles ($r_0 \sim 0{\cdot}05$ μm), with an increase in μ_0 scattering approaches isotropic one (Fig. 8a, b). For more coarse modal sizes (Fig. 8d) almost the whole energy dissipated by a unit volume stretches into a narrow beam directed exactly forward, i.e. scattering does not practically contribute to net radiant attenuation. Radiant attenuation occurs only due to absorption. As the wavelength λ increases, the scattering indicatrix becomes less advanced (Fig. 8c).

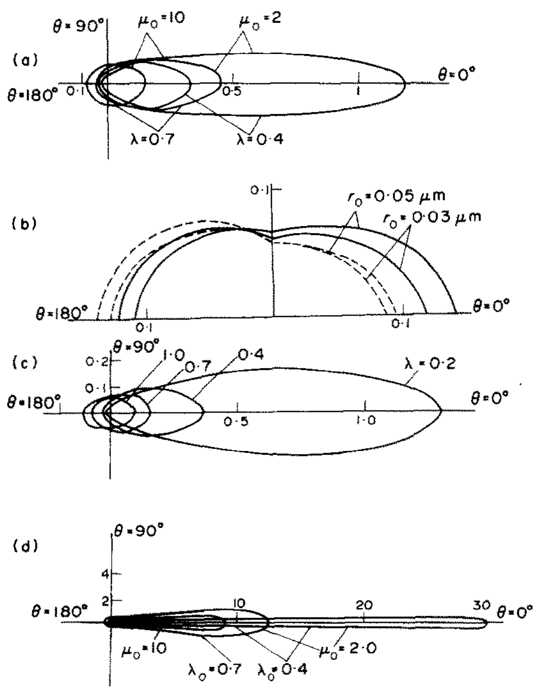

FIG. 8. Shape of scattering indicatrices of polydisperse media: a, b—for fine particles, $r_0 \leqslant 0{\cdot}1$ μm; c—vs wavelength λ; d—for coarse particles, $r_0 = 0{\cdot}6$ μm.

2. CALCULATION METHOD FOR RADIANT FLUXES IN DISPERSE MEDIA

In the radiant heat-transfer theory different methods, both approximate and exact, which refer to the class either of differential or of integral ones, are developed to solve the radiation transfer equation. The both classes are being developed simultaneously by various workers. However, application of the integral methods to the radiation transfer equation does not allow frequently its solution to be obtained in the analytical form, and much computer time is needed to get a numerical solution. Therefore, together with the integral methods the simple approximate differential ones should be developed for radiant heat transfer. The advantage of the former is relative simplicity, the possibility to describe the problem by the well-known class of differential equations which are fairly coupled with those for heat conduction and convective heat transfer when solving complex heat transfer problems.

2.1. *Parallel-plane bed*

During the recent years wide use has been made of the moment method and its modifications [8–10] which allows the equations for radiant flux q_{R_λ} or its components to be obtained based on the appropriate integration of the radiation transfer equation. Good accuracy of this method [8] is obtained when applied, to a first approximation, to an isotropically scattering medium. The calculation method of radiant fluxes, equivalent to the first approximation of the moment method [9], was proposed for anisotropically scattering media with the arbitrary indicatrix. However, in deriving the equation for q_{R_λ} the discontinuity of $I_\lambda(\tau_\lambda, \mu)$ at $\mu = 0$ was not accounted for. In addition, only the first term a_1 of scattering indicatrix expansion into the Legendre polynomials regards for the scattering indicatrix effect upon the radiant flux. In such a case the value of the radiant flux is not always obtained with sufficient accuracy, especially in case of a far advanced scattering indicatrix.

The present work deals with the method of calculation of radiant heat transfer in the parallel-plane bed of absorbing, radiating and anisotropically scattering media. This method is a modification of the spherical harmonic method which was first proposed by Ivon [11] for solution of neutron transfer equations. To a first approximation, the system of ordinary differential fourth-order equations is obtained for radiant fluxes. This system allows for any numbers of the terms of scattering indicatrix expansion into the Legendre polynomials.

Consider a parallel-plane suspension bed bounded by diffusely emitting surface. The radiation transfer equation for the spectral radiation intensity independent of the asimuthal angle φ has the form:

$$\mu\frac{\partial I_\lambda(\tau_\lambda,\mu)}{\partial\tau_\lambda} + I(\tau_\lambda,\mu) = (1-\omega_\lambda)I_{B_\lambda}(T) + \frac{\omega_\lambda}{2}\int_{-1}^{1} P(\mu,\mu')I_\lambda(\tau_\lambda,\mu')\,\mathrm{d}\mu'. \quad (5)$$

The boundary conditions at the surfaces with temperatures T_i $(i = 1, 2)$ and emissivity ε_i are as follows:

$$\tau_\lambda = 0;\ I_\lambda^+(\tau_\lambda, \mu) = \varepsilon_{\lambda 1} I_{B_\lambda}(T_1) + 2(1-\varepsilon_{\lambda 1}) \int_0^{-1} I_\lambda^-(0, \mu)\mu\, d\mu$$
$$\tau_\lambda = \tau_{0\lambda};\ I_\lambda^-(\tau_\lambda, \mu) = \varepsilon_{\lambda 2} I_{B_\lambda}(T_2) + 2(1-\varepsilon_{\lambda 2}) \int_0^{1} I_\lambda^+(\tau_{0\lambda}, \mu)\mu\, d\mu, \quad (6)$$

where $I_\lambda^\pm(\tau_\lambda, \mu)$ are intensities at positive and negative μ.

The calculation method for radiant fluxes is based on the concept of the radiation intensity in terms of the Legendre polynomials series. Here, because of the discontinuity of $I_\lambda(\tau_\lambda, \mu)$ at $\mu = 0$ two different series are used:

$$I_\lambda^\pm(\tau_\lambda, \mu) = \frac{1}{4\pi} \sum_{i=0}^{\infty} (2i+1) I_i^\pm(\tau_\lambda) P_i(2\mu \mp 1). \quad (7)$$

Series (7) allows a sufficiently simple expression to be obtained for the radiant flux:

$$q_{R_\lambda} = 2\pi \int_{-1}^{1} I(\tau_\lambda, \mu)\mu\, d\mu = \tfrac{1}{4}\{[I_0^+(\tau_\lambda) - I_0^-(\tau_\lambda)] + [I_1^+(\tau_\lambda) + I_1^-(\tau_\lambda)]\} = \tfrac{1}{4}\{l_1(\tau_\lambda) + l_2(\tau_\lambda)\}. \quad (8)$$

Substitution of expression (7) into radiation transfer equation (5) and some mathematical transformations [12] result in the system:

$$\alpha_{ik} \frac{dI_i^+(\tau_\lambda)}{d\tau_\lambda} + \beta_{ik} I_i^+(\tau_\lambda) = 4\pi(1-\omega_\lambda)\delta_{0k} I_{B_\lambda}(T) + \frac{\omega_\lambda}{2}\{I_i^+(\tau_\lambda)\gamma_{+i+k} + I_i^-(\tau_\lambda)\gamma_{-i+k}\};$$
$$(-1)^{i+k+1}\alpha_{ik} \frac{dI_i^-(\tau_\lambda)}{d\tau_\lambda} + \beta_{ik} I_i^-(\tau_\lambda) = 4\pi(1-\omega_\lambda)\delta_{0k} I_{B_\lambda}(T) + \frac{\omega_\lambda}{2}\{I_i^+(\tau_\lambda)\gamma_{+i-k} + I_i^-(\tau_\lambda)\gamma_{-i-k}\}$$
$$(i, k = 0, 1, 2, \ldots) \quad (9)$$

under the boundary conditions for the series moments $I_i^\pm(\tau_\lambda)$:

$$\tau_\lambda = 0:\ \beta_{ik} I_i^+(0) = 4\pi\varepsilon_{\lambda 1} I_{B_\lambda}(T_1)\delta_{0k} + 2(1-\varepsilon_{\lambda 1}) I_i^-(0)\alpha_{i0}\delta_{0k}$$
$$\tau_\lambda = \tau_{0\lambda}:\ \beta_{ik} I_i^-(\tau_{0\lambda}) = 4\pi\varepsilon_{\lambda 2} I_{B_\lambda}(T_2)\delta_{0k} + 2(1-\varepsilon_{\lambda 2}) I_i^+(\tau_{0\lambda})\alpha_{i0}\delta_{0k} \quad (10)$$

Here

$$\alpha_{ik} = \begin{cases} \dfrac{i}{2}, & k = i-1 \\ \dfrac{2i+1}{2}, & k = i \\ \dfrac{i+1}{2}, & k = i+1 \\ 0, & k > i+1,\ k < i-1 \end{cases} \qquad \beta_{ik} = \begin{cases} 0, & i \neq k \\ 2i+1, & i = k. \end{cases} \quad (11)$$

The coefficient matrix

$$\gamma_{+i+k} = (2i+1)(2k+1) \int_0^1 d\mu \int_0^1 P_k(2\mu-1) \times P_i(2\mu'-1) P(\mu, \mu')\, d\mu'$$
$$\gamma_{+i-k} = (2i+1)(2k+1) \int_{-1}^0 d\mu \int_0^1 P_k(2\mu+1) \times P_i(2\mu'-1) P(\mu, \mu')\, d\mu'$$
$$\gamma_{-i+k} = (2i+1)(2k+1) \int_0^1 d\mu \int_{-1}^0 P_k(2\mu-1) \times P_i(2\mu'+1) P(\mu, \mu')\, d\mu'$$
$$\gamma_{-i-k} = (2i+1)(2k+1) \int_{-1}^0 d\mu \int_{-1}^0 P_k(2\mu+1) \times P_i(2\mu'+1) P(\mu, \mu')\, d\mu' \quad (12)$$

possesses symmetry properties:

1. $\gamma_{\pm i \pm k} = \gamma_{\pm k \pm i}$
2. $\gamma_{+0+k} + \gamma_{-0+k} = \begin{cases} 2, & k = 0 \\ 0, & k \geqslant 1 \end{cases}$
   $\gamma_{-0+k} + \gamma_{-0-k} = \begin{cases} 2, & k = 0 \\ 0, & k \geqslant 1 \end{cases}$ (13)
3. $\gamma_{-i-k} = (-1)^{i+k}\gamma_{+i+k}$
   $\gamma_{+i-k} = (-1)^{i+k}\gamma_{-i+k}$.

With a finite number M in series (7) taken, system (9) of $2(M+1)$ equations is obtained for $I_i^\pm(\tau_\lambda)$.

It should be noted that at $M = 0$ system (9) at boundary conditions (10) coincides with the known Schwartzschield–Schuster approximation. The radiant flux to this approximation is given by:

$$q_{R_\lambda} = \tfrac{1}{4}[I_0^+(\tau_\lambda) - I_0^-(\tau_\lambda)] = \tfrac{1}{4} l_1(\tau_\lambda). \quad (14)$$

At $M = 1$, upon some transformations of system (9) with relations (11)–(13), the system of ordinary differential fourth-order equations with constant coefficients is got to calculate radiant heat transfer:

$$\frac{dl_1(\tau_\lambda)}{d\tau_\lambda} = A_1 l_3(\tau_\lambda) + A_2 l_4(\tau_\lambda) + 24\pi(1-\omega_\lambda) I_{B_\lambda}(T)$$
$$\frac{dl_2(\tau_\lambda)}{d\tau_\lambda} = A_3 l_3(\tau_\lambda) + A_4 l_4(\tau_\lambda) - 8\pi(1-\omega_\lambda) I_{B_\lambda}(T)$$
$$\frac{dl_3(\tau_\lambda)}{d\tau_\lambda} = A_5 l_1(\tau_\lambda) + A_6 l_2(\tau_\lambda) \quad (15)$$
$$\frac{dl_4(\tau_\lambda)}{d\tau_\lambda} = A_7 l_1(\tau_\lambda) + A_8 l_2(\tau_\lambda)$$

where

$$l_3(\tau_\lambda) = I_0^+(\tau_\lambda) + I_0^-(\tau_\lambda), \quad l_4(\tau_\lambda) = I_1^+(\tau_\lambda) - I_1^-(\tau_\lambda)$$

The coefficients of system A_i depend on parameter ω_λ and coefficients of expansion into the Legendre polynomial series of the scattering indicatrix a_i:

$$A_1 = 3(\omega_\lambda - 1)$$
$$A_2 = \tfrac{1}{2}[6 - \omega_\lambda(\gamma_6 - \gamma_5)]$$
$$A_3 = 1 - \omega_\lambda$$
$$A_4 = -A_2$$
$$A_5 = \tfrac{1}{2}[3\omega_\lambda(\gamma_1 - \gamma_2) - 2\omega_\lambda\gamma_3 - 6]$$
$$A_6 = \tfrac{1}{2}[6\omega_\lambda\gamma_3 - \omega_\lambda(\gamma_6 + \gamma_5) + 6]$$
$$A_7 = \tfrac{1}{2}[\omega_\lambda(\gamma_3 + \gamma_4) - \omega_\lambda(\gamma_1 - \gamma_2) + 2]$$
$$A_8 = \tfrac{1}{2}[\omega_\lambda(\gamma_5 + \gamma_6) - \omega_\lambda(\gamma_3 + \gamma_4) - 6]$$
$$\gamma_1 = 1 + \tfrac{1}{4}a_1 + \tfrac{1}{64}a_3 + \tfrac{1}{256}a_5, \quad \gamma_2 = 2 - \gamma_1$$
$$\gamma_3 = 3(1 - \gamma_1 + \tfrac{1}{3}a_1), \quad \gamma_4 = \gamma_3$$
$$\gamma_6 = 9[\gamma_1 - 2(1 + \tfrac{1}{3}a_1)] + 36\left[\tfrac{1}{4} + \frac{1}{9}a_1 + \tfrac{1}{64}a_2 + \tfrac{1}{2304}a_4\right]$$
$$\gamma_5 = 2a_1 - \gamma_6.$$

In the above formulae the number of the terms for scattering indicatrix series is limited to $l = 5$ since such indicatrices are of greatest interest.

Boundary conditions (10) closing system (15) may be reduced to:

$$\tau_\lambda = 0;\ l_2 + l_4 = 0,$$
$$l_1 + l_3 = 8\pi\varepsilon_{\lambda 1} I_{B_\lambda}(T_1) + (1-\varepsilon_{\lambda 1})(l_3 - l_1) \quad (16)$$
$$\tau_\lambda = \tau_{0\lambda};\ l_2 - l_4 = 0,$$
$$l_3 - l_1 = 8\pi\varepsilon_{\lambda 2} I_{B_\lambda}(T_2) + (1-\varepsilon_{\lambda 2})(l_3 + l_1)$$

As has earlier been shown [12], based on system (15)–(16) calculation of radiant fluxes ensures good accuracy of the method. Comparison of the expressions for exact radiant flux (8) with the Schwartzschield–Schuster approximation (14) shows that the difference lies in the terms $I_1^+(\tau_\lambda) + I_1^-(\tau_\lambda)$ which is neglected at $M = 0$. This is the reason of insufficient accuracy of the Schwartzschield–Schuster approximation in many cases. The approximation $M = 1$ eliminates this drawback.

The spectral radiant fluxes in absorbing and scattering media were calculated to analyze the effect of scattering parameters and the medium microstructure upon radiant attenuation:

$$\bar{q}_{R_\lambda} = \frac{q_{R_\lambda}}{\pi I_{0\lambda}} \quad (\lambda = 0{\cdot}3\ \mu\text{m}).$$

Solution of system (15) with the boundary conditions

$$\tau_\lambda = 0;\ l_2 + l_4 = 0, \quad l_1 + l_3 = 8\pi I_{0\lambda}$$
$$\tau_\lambda = \tau_{0\lambda};\ l_2 - l_4 = 0, \quad l_3 - l_1 = 0$$

obtained from the appropriate boundary conditions for radiation intensity gives:

$$I_\lambda(0,\mu)|_{\mu>0} = I_{0\lambda}$$
$$I_\lambda(\tau_{0\lambda},\mu)|_{\mu<0} = 0.$$

The data on attenuation coefficients k'_λ and scattering indicatrices used in the calculations are given in Table 1. In all cases the weight particle concentration γ used for calculationg optical thicknesses

$$\tau_{0\lambda} = \tfrac{3}{4}\frac{\gamma}{d} k'_\lambda L$$

was constant and equal to $\gamma = 0{\cdot}2 \times 10^{-3}\ \text{g/cm}^3$.

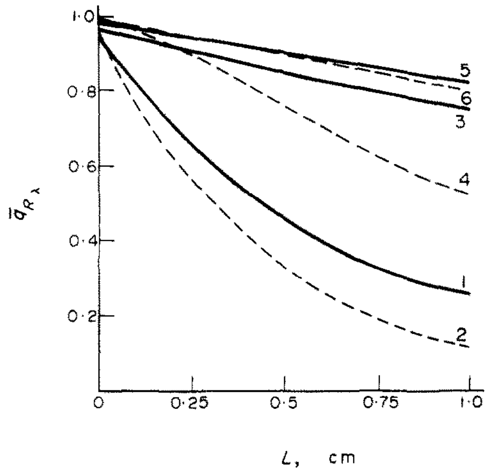

FIG. 9. Radiant flux distribution q_R over the bed $L = 1$ cm with (curves 1, 3, 5) and without scattering (curves 2, 4, 6).

Figure 9 gives comparison of radiant flux attenuation with (curves 1, 3) and without scattering (curves 2, 4). For fine particles $r_0 = 0{\cdot}1\ \mu$m (curves 1, 2) a large correction for scattering is introduced into the radiant flux. For more coarse particles $r_0 \approx 0{\cdot}4\ \mu$m the effect of scattering is less essential. When the modal radius increases, the curves for real values of ω_λ and $\omega_\lambda = 0$ practically coincide (curves 5, 6). For the media with

$$\rho_0 = \frac{2\pi r_0}{\lambda} > 6$$

radiant fluxes may be calculated with sufficient accuracy when scattering is neglected which is very important since in such cases scattering indicatrices should not be necessarily found. Replacement of a real indicatrix of unit volume scattering by an isotropic one slightly influences the value of the radiant flux in the media with fine particles (Fig. 10). With an increase in r_0 the error of radiant fluxes grows when real scattering is replaced by isotropic one. The calculations have shown that this error is 30 per cent and more for the media with $\rho_0 > 6$. Figure 11 gives the effect of the parameter r_0 on radiant flux attenuation. Curve 3 describes radiant flux attenuation at $r_0 = 0{\cdot}2\ \mu$m. Once each particle is 4 times decreased at the same concentration, radiant flux attenuation due to such decrease is increased by 4 times (curve 1).

Table 1.

No.	μ_0	r_0 (μm)	k'_λ (m^{-1})	ω_λ	a_1	a_2	a_3	a_4
1	6	0·1	17·82	0·66	0·42	0·52	0·46	0·31
2	6	0·4	3·88	0·71	1·82	2·78	3·42	0·71
3	6	0·1	17·82	0·66	0	0	0	0
4	6	0·4	3·88	0·71	0	0	0	0
5	2	0·1	10·16	0·68	0·69	0·95	1·01	0·89
6	2	0·05	21·71	0·64	0·35	0·41	0·34	0·21
7	2	0·2	4·75	0·70	2·47	3·77	4·63	5·00
8	4	0·1	15·03	0·66	0·49	0·63	0·600	0·45
9	10	0·1	20·87	0·65	0·37	0·43	0·35	0·20

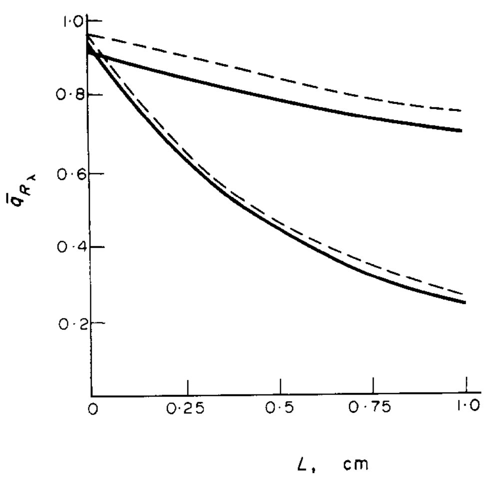

FIG. 10. Effect of scattering indicatrix on $\bar{q}_{R_\lambda}$. Solid curves represent real indicatrices; dashed ones, isotropic scattering.

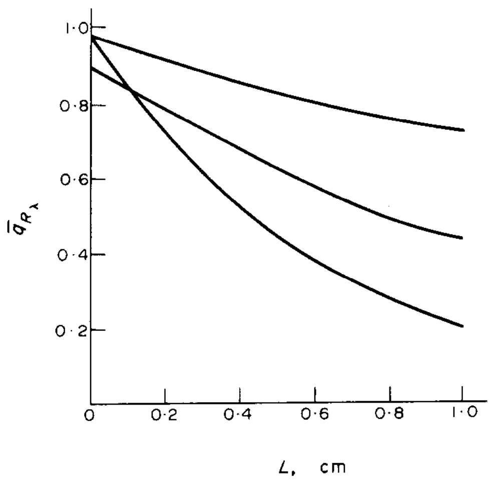

FIG. 11. Effect of parameter r_0 on attenuation of radiant flux q_{R_λ}: $1-r_0 = 0{\cdot}05$; $2-r_0 = 0{\cdot}1$; $3-r_0 = 0{\cdot}2$ for $\mu_0 = 2$.

2.2. *Spherically symmetric bed*

The regularities of radiant energy transfer under spherical symmetry conditions are of great practical interest and have intensively been studied during the recent years. The problem on radiant flux in the space between concentric spheres was solved for grey absorbing and emitting media by numerical integration of the exact integral equations, for example [14–16], and by use of the approximate differential equations [16–19] obtained from the classical moment method or its modifications as well as from some other differential approximations [20–22], which have not much in common, that hampers their application.

In all the above works anisotropic scattering of media is not considered. In the present work, within the classical spherical harmonics method the radiant flux equation is obtained for absorbing, emitting and anisotropically scattering media, that allows for scattering to a first approximation, i.e. only the first coefficient in the Legendre polynomial series of the scattering indicatrix is taken into account. The approximate differential equation for purely absorbing media is the Miln–Eddington approximation for spherical symmetry. This approximation when applied to purely absorbing media has some disadvantages. In [23] use of the differential approximation for the problems with non-plane geometry was considered. It was there shown that once sphere surface temperatures are not the same, the differential approximation appears non-exact in the extreme case of optically thin gas. Moreover, this approximation does not permit the shadow effect from the inner sphere to be accounted for. However, as will be shown later, the approximate equation for intermediate values of optical thicknesses, where, unlike optically thin beds, scattering plays a very essential role, permits radiant fluxes to be determined with sufficient accuracy.

A physical model of the problem considered consists of two non-transparent spheres with inner radius r_1 and outer radius r_2. The intermediate space between them is filled with absorbing, emitting and scattering grey media with constant attenuation coefficients uniform across the medium. The opaque walls with the emissivity ε_i $(i = 1, 2)$ uniform over the surface are assumed diffusely radiating. The radiation transfer equation may be written as:

$$\mu\frac{\partial I(r,\mu)}{\partial r}+\frac{1-\mu^2}{r}\frac{\partial I(r,\mu)}{\partial \mu} = -kI(r,\mu)+\alpha I_B(r) + \frac{\beta}{2}\int_{-1}^{1} I(r,\mu')P(\mu,\mu')\,d\mu'. \quad (17)$$

The boundary conditions for intensity at the opaque diffuse walls may be written as:

$$I(r_1,\mu)|_{\mu>0} = \varepsilon_1 I_B(T_1) + (1-\varepsilon_1)\int_0^{-1} I(r_1,\mu)|_{\mu<0}\,\mu\,d\mu$$

$$I(r,\mu)|_{\mu<0} = \varepsilon_2 I_B(T_2) + (1-\varepsilon_2)\int_0^{1} I(r_2,\mu)|_{\mu>0}\,\mu\,d\mu. \quad (18)$$

Let the intensity be given in the form:

$$I(r,\mu) = \frac{1}{4\pi}\sum_{i=0}^{\infty}(2i+1)I_i(r)P_i(\mu). \quad (19)$$

Substituting series (19) into equation (17), multiplying the both sides of the equation by $(2k+1)P_k(\mu)$ where $k = 0, 1, 2, \ldots$ and integrating within $-1 \leqslant \mu \leqslant 1$, we get an infinite system of equations for the moments $I_i(r)$:

$$\alpha_{ik}\frac{dI_i(r)}{dr}+\left[\frac{\alpha_{ik}^*}{r}+k\beta_{ik}-\beta a_i\beta_{ik}\right]I_i(r) = 4\pi\alpha\beta_{0k}I_B(r) \quad (20)$$

where the coefficients α_{ik}, α^*_{ik} and β_{ik} upon some transformations become:

$$\alpha_{ik} = \begin{cases} 2(i+1), & k = i+1 \\ 2i, & k = i-1 \\ 0, & k \neq i+1, \quad k \neq i-1 \end{cases}$$

$$\alpha^*_{ik} = \begin{cases} 2i(i+1), & k = i-1 \\ -2i(i+1), & k = i+1 \\ 0, & k \neq i-1, \quad k \neq i+1 \end{cases} \tag{21}$$

$$\beta_{ik} = \begin{cases} 2, & k = i \\ 0, & k \neq i. \end{cases}$$

With regard for series (19) the radiant flux may be expressed in terms of the first moment $I_1(r)$

$$q_R = 2\int_{-1}^{1} I(r,\mu)\mu\,\mathrm{d}\mu$$
$$= \tfrac{1}{2}\sum_{i=0}^{\infty}(2i+1)I_i(r)\int_{-1}^{1} P_i(\mu)\mu\,\mathrm{d}\mu = I_1(r).$$

The infinite system of equations (20) should be solved to find $I_1(r)$, that is impossible. A finite system of $(M+1)$ equations is got by limiting M terms in series (19). The approximation $M = 1$ will be only considered. Then, from expressions (21) we may write the coefficients of system (20) as:

$$\alpha_{00} = \alpha_{11} = \alpha^*_{00} = \alpha^*_{11} = \alpha^*_{01} = 0, \quad \alpha_{10} = \alpha_{01} = 2,$$
$$\alpha^*_{10} = 4, \quad \beta_{10} = \beta_{01} = 0, \quad \beta_{00} = 2, \quad \beta_{11} = 6.$$

In this case equations (20) will be a system of two equations:

$$\frac{\mathrm{d}I_1(r)}{\mathrm{d}r} + \frac{2}{r}I_1(r) = -\alpha I_0(r) + 4\pi\alpha I_B(r)$$
$$\frac{\mathrm{d}I_0(r)}{\mathrm{d}r} = (\beta a_1 - 3k)I_1(r). \tag{21}$$

Hence, differentiating the first equation and substituting for $\mathrm{d}I_0(r)/\mathrm{d}r$ from the second equation we arrive at the second-order equation for the radiant flux

$$r^2\frac{\mathrm{d}^2I_1(r)}{\mathrm{d}r^2} + 2r\frac{\mathrm{d}I_1(r)}{\mathrm{d}r} - (ar^2+2)I_1(r) = 4\pi\alpha I'_B(r)r^2, \tag{22}$$

where $a = \alpha(3k - \beta a_1) > 0$, since $a_1 \leq 3$. The above approximate equation for radiant flux in scattering media differs from the Miln–Eddington approximation for purely absorbing media

$$\frac{\mathrm{d}^2q_R(r)}{\mathrm{d}r^2} + \frac{2}{r}q_R(r) - \left(3\alpha + \frac{2}{r^2}\right)q_R(r) = 4\pi\alpha I'_B(r)$$

only by the coefficient a, which is equal to $3\alpha^2$ for absorbing media. With regard for scattering, the coefficient a also depends both on ω_0 and the shape of the scattering indicatrix, i.e. on a_1.

Unlike the moment method for half-spaces which allows direct determination of exact boundary conditions, series (19) gives approximate boundary conditions for equation (22). That these conditions be obtained, we should proceed from the boundary conditions for the radiant flux

$$r = r_1;\ 2\pi\int_0^1 I(r,\mu)\mu\,\mathrm{d}\mu = \varepsilon_1\pi I_B(T_1) + (1-\varepsilon_1)2\pi\int_0^{-1} I(r_1,\mu)\mu\,\mathrm{d}\mu$$
$$r = r_2;\ 2\pi\int_0^{-1} I(r,\mu)\mu\,\mathrm{d}\mu = \varepsilon_2\pi I_B(T_2) + (1-\varepsilon_2)2\pi\int_0^1 I(r_2,\mu)\mu\,\mathrm{d}\mu, \tag{23}$$

corresponding to the boundary conditions (18) for intensities. Substitution of series (19) into equation (23) and term-by-term integration at $M = 1$ yield:

$$\text{at } r = r_1;\ \varepsilon_1 I_0(r) + 2(2-\varepsilon_1)I_1(r) = 4\varepsilon_1\pi I_B(T_1)$$
$$\text{at } r = r_2;\ \varepsilon_2 I_0(r) - 2(2-\varepsilon_2)I_1(r) = 4\varepsilon_2\pi I_B(T_2). \tag{24}$$

Boundary conditions (24) for black surfaces were originally obtained by Chang [24] and may be considered the extension of Eddington's method. Chisnell [25] has obtained the same relations assuming semi-isotropic radiation intensity of the wall. Substituting for $I_0(r)$ its expression from the first equation of system (22) at $r = r_1$ and $r = r_2$ into (24) gives the following boundary conditions for equation (22):

$$r = r_1;\ \left[2(2-\varepsilon_1) - \frac{2\varepsilon_1}{r_1\alpha}\right]I_1(r) - \frac{\varepsilon_1}{\alpha}\frac{\mathrm{d}I_1(r)}{\mathrm{d}r} = 0$$
$$r = r_2;\ \left[2(2-\varepsilon_2) + \frac{2\varepsilon_2}{r_2\alpha}\right]I_1(r) + \frac{\varepsilon_2}{\alpha}\frac{\mathrm{d}I_1(r)}{\mathrm{d}r} = 0. \tag{25}$$

Thus, radiant flux is found from the solution of the ordinary inhomogeneous differential equation of second order (22) with boundary conditions (25).

Consider the problem which corresponds to the physical model described earlier in this paper. A heat-conducting medium is assumed in addition.

The energy conservation equation for radiant-convective heat transfer and spherical symmetry has the form:

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left\{r^2\left[\lambda\frac{\mathrm{d}T(r)}{\mathrm{d}r} - I_1(r)\right]\right\} = 0 \tag{26}$$

where λ is the thermal conductivity of the medium.

The boundary conditions are as follows:

$$\text{at } r = r_1;\ T = T_1$$
$$\text{at } r = r_2;\ T = T_2.$$

Introduce dimensionless radiant flux $P = (I_1/\sigma T_*^4)$, temperature $\Theta = T/T_*$ and radius $\xi = r/r_2$ where T_* is some characteristic temperature.

Upon integration equation (26) in a dimensionless form may be written as:

$$\frac{d\Theta(\xi)}{d\xi} = \frac{\tau_2 P(\xi)}{4N} + \frac{C}{\xi^2} \tag{27}$$

where C is the integration constant.

$$N = \frac{\lambda k}{4\sigma T_*^3}, \quad \tau_2 = kr_2$$

Solution of equation (27) at the boundary conditions

$$\xi = \xi_1 = \frac{r_1}{r_2}; \quad \Theta = \Theta_1$$

$$\xi = 1; \qquad \Theta = \Theta_2$$

gives the following integral expression for a temperature θ:

$$\Theta(\xi) = \frac{1}{\xi_1 - 1}\left\{\xi_1 \Theta_1\left(1 - \frac{1}{\xi}\right) + \Theta_2\left(\frac{\xi_1}{\xi} - 1\right)\right\} + \frac{\xi_1 \tau_2}{4N}\int_{\xi_1}^{\xi} P(\xi)\,d\xi + \frac{\tau_2}{4N}\int_{\xi}^{1} P(\xi)\,d\xi - \frac{\xi_1 \tau_2}{4N\xi}\int_{\xi_1}^{1} P(\xi)\,d\xi \tag{28}$$

Let us find the expression for radiant flux $P(\xi)$ from equation (22) which was preliminarily brought to a dimensionless form by dividing the both sides by σT_*^4 and by introducing new variable ξ. Since the identities

$$ar_2^2 = (\omega_0 - 1)(\omega_0 a_1 - 3)\tau_2^2 = a^*$$

$$\alpha r_2 = (1 - \omega_0)\tau_2,$$

are valid, equation (22) is reduced to:

$$\frac{d^2 P(\xi)}{d\xi^2} + \frac{2}{\xi}\frac{dP(\xi)}{d\xi} - \left(a^* + \frac{2}{\xi^2}\right)P(\xi) = 16(1 - \omega_0)\tau_2 \theta^3(\xi)\frac{d\theta(\xi)}{d\xi}. \tag{29}$$

The above boundary conditions are accordingly written in a dimensionless form as:

$$\xi = \xi_1;\ \left[2(2 - \varepsilon_1) - \frac{2\varepsilon_1}{(1 - \omega_0)\xi_1 \tau_2}\right]P(\xi) - \frac{\varepsilon_1}{(1 - \omega_0)\tau_2}\frac{dP(\xi)}{d\xi} = 0$$

$$\xi = 1;\ \left[2(2 - \varepsilon_2) + \frac{2\varepsilon_2}{(1 - \omega_0)\tau_2}\right]P(\xi) + \frac{\varepsilon_2}{(1 - \omega_0)\tau_2}\frac{dP(\xi)}{d\xi} = 0. \tag{30}$$

Formal solution of problem (29)–(30) by the variational method of arbitrary constant (26) results in the expression for the radiant flux:

$$P(\xi) = \frac{16(1 - \omega_0)\tau_2}{\Delta\sqrt{a_*}}\left\{\varphi_1(\xi)\left[b_1 d_2 \int_{\xi_1}^{\xi} \xi^2 \varphi_2(\xi)\Theta^3(\xi)\Theta^1(\xi)\,d\xi + d_1 b_2 \int_{\xi}^{1} \xi^2 \varphi_2(\xi)\Theta^3(\xi)\Theta^1(\xi)\,d\xi + d_1 d_2 \int_{\xi_1}^{1} \xi^2 \varphi_1(\xi)\Theta^3(\xi)\Theta^1(\xi)\,d\xi\right]\right.$$

$$+ \varphi_2(\xi)\left[b_1 d_2 \int_{1}^{\xi} \xi^2 \varphi_1(\xi)\Theta^3(\xi)\Theta^1(\xi)\,d\xi - b_2 d_1 \int_{\xi_1}^{\xi} \xi^2 \varphi_1(\xi)\Theta^3(\xi)\Theta^1(\xi)\,d\xi \left. - b_1 b_2 \int_{\xi_1}^{1} \xi^2 \varphi_2(\xi)\Theta^3(\xi)\Theta^1(\xi)\,d\xi\right]\right\} \tag{31}$$

where

$$\varphi_1(\xi) = \frac{\sinh(\sqrt{a^*})\xi}{(\sqrt{a^*})\xi^2} - \frac{\cosh(\sqrt{a^*})\xi}{\xi}$$

$$\varphi_2(\xi) = \frac{\cosh(\sqrt{a^*})\xi}{(\sqrt{a^*})\xi^2} - \frac{\sinh(\sqrt{a^*})\xi}{\xi}$$

$$b_1 = A_1\varphi_1(\xi_1) - B_1\varphi_1^1(\xi_1),$$

$$d_1 = A_1\varphi_2(\xi_1) - B_1\varphi_2^1(\xi_1)$$

$$b_2 = A_2\varphi_1(1) + B_2\varphi_1^1(1),$$

$$d_2 = A_2\varphi_2(1) + B_2\varphi_2^1(1)$$

$$A_1 = 2(2 - \varepsilon_1) - \frac{2\varepsilon_1}{(1 - \omega_0)\xi_1 \tau_2}$$

$$B_i = \frac{\varepsilon_i}{(1 - \omega_0)\tau_2}$$

$$A_2 = 2(2 - \varepsilon_2) + \frac{2\varepsilon_2}{(1 - \omega_0)\tau_2}$$

$$\Delta = b_1 d_2 - d_1 b_2$$

The system of integral equations (28), (31) for the fields of temperatures and radiant fluxes was numerically solved by the iteration procedure on the computer M-220.

At first, system (28), (31) was solved for purely absorbing media at the following parameters: $\varepsilon_1 = \varepsilon_2 = 1{\cdot}0$

$$\Theta_1 = 1{\cdot}0;\ \Theta_2 = 0{\cdot}5;\ \tau_2 = 2{\cdot}0;\ \xi_1 = \{0{\cdot}1 - 0{\cdot}95\},\ N = 0{\cdot}1$$

for comparison with the exact solution of the heat-conduction equation together with the radiation transfer equation of [26]. Figures 12 and 13 give plots of temperature profiles and radiant fluxes at dimensionless distances $(r - r_1)/(r_2 - r_1)$ vs the surface geometry

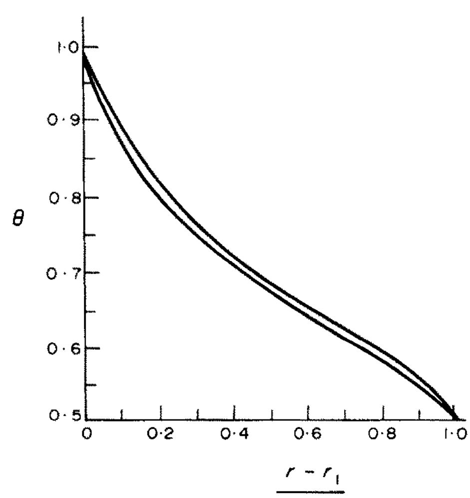

FIG. 12. Plot of temperature vs geometry factor: 1—from equations (28), (31); 2—according to data of [26].

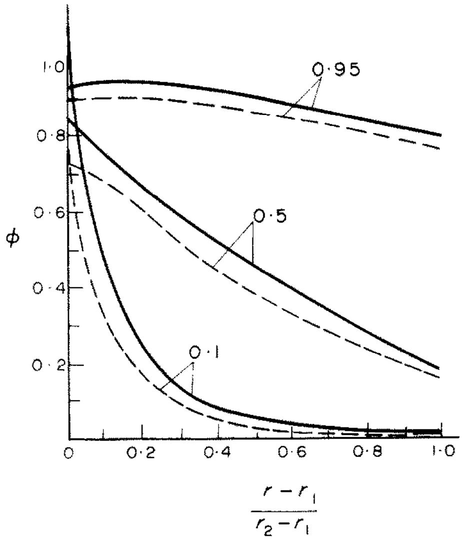

FIG. 13. Radiant flux distribution $P(\xi)$: solid lines—from equations (28), (31); dashed lines—data of [26].

factor $\xi_1 = r_1/r_2$. Comparison of these plots with the data of [26] (dashed lines) shows the greatest deviations of the radiant fluxes calculated to a first approximation by the moment method from their exact values at small ξ_1. In these very cases are observed physically senseless results obtained by the moment method for radiant fluxes in spherical symmetry, i.e. the values of $P(\xi_1) > 1$. As far as $\xi_1(\xi_1 > 0{\cdot}1)$ increases and the distance between spheres decreases, this effect is not observed. The calculations were made of black walls, therefore, for $\varepsilon_i < 1$ the ranges of applicability of the moment method for ξ_1 may be extended. Comparison of temperature distributions obtained to the approximation of the moment method with the exact values shows that the moment method gives good accuracy of temperature calculations. Although the method proposed gives overestimated values of radiant fluxes, usage of simple equation (22) seems more advisable compared to the complicated radiation transfer equation.

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ATTENUATION DU RAYONNEMENT EN MILIEU DISPERSIF

Résumé—Les coefficient volumétriques d'atténuation et de diffusion sont analysés, ainsi que les indicatrices de diffusion du milieu dispersif avec additions métalliques. Des méthodes pour le calcul des flux de rayonnement dans les milieux diffusifs anisotropes sont proposées pour des surfaces planes parallèles et à symétrie sphérique. On étudie l'influence des paramètres de la microstructure du milieu sur les flux de rayonnement.

STRAHLUNGSDÄMPFUNG DURCH DISPERGIERTES MEDIUM

Zusammenfassung—Es werden die volumetrischen Koeffizienten der Dämpfung, der Streuung und die Streuungsindikatrix von dispergierten Medien mit metallischen Zusätzen untersucht. Methoden zur Berechnung von Strahlungseinflüssen in anisotropen streuenden Medien werden für ebene parallele und sphärisch symmetrische Schichten vorgeschlagen. Die Auswirkung der Parameter eines mittleren Feingefüges auf die Strahlung wird erforscht.

ОСЛАБЛЕНИЕ РАДИАЦИИ ДИСПЕРСНЫМИ СРЕДАМИ

Аннотация — Анализируются объёмные коэффициенты ослабления и рассеяния, а также индикатрисы рассеяния дисперсных сред с металлическими добавками. Предлагаются методы расчёта интенсивности потока излучения в анизотропно-рассеивающих средах для параллельно-плоскостных и сферически-симметричных слоев. Рассматривается влияние параметров микроструктуры среды на интенсивность потока излучения.