RADIATION PROPAGATION THROUGH SPATIALLY BOUNDED MEDIA WITH HIGH CONCENTRATION OF SCATTERERS

B.V. Goryachev, M.V. Kabanov, and S.B. Mogil'nitskii

Tomsk Polytechnic University
Design and Technology Institute "Optika,"
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received June 27, 1995

The brightening effect attendant to the radiation propagation through a densely packed disperse medium has been investigated. The range of variation of the optical parameters of the disperse medium has been investigated, in which this effect is primarily determined by spatial boundedness of the medium.

The study of the brightening effect attendant to the radiation propagation through a medium with high volume concentration of scatterers is an urgent problem.[1–4] This phenomenon is studied by various techniques, for example, it can be judged by the deviation from Bouguer's law, change in the scattering phase function, light radiation measurements, changes in absolute values of reflected and transmitted light radiation, etc. At first sight physics of the phenomenon is quite apparent: when the distance between particles is large, a major portion of radiation leaves the medium without interaction with particles. Conversely, for a closely packed ensemble of particles, all radiation interacts with it. The number of interacting photons however may vary not only with the particle concentration, but also with the transverse optical depths of a medium. This is proved by the fact that the transmittance of a layer of fixed thickness increases (it brightens) as its transverse optical depths are increased.

Thus it becomes apparent that to account for such facts as these, the notion of spatial boundedness effect (SBE) must be introduced in addition to the interference and cooperation effects widely covered in the literature. This effect manifests itself in transmittance and reflectance variations due to varying transverse (with respect to the direction of propagation) depths of disperse medium and depends on its parameters and radiation properties. Major contributors to the reflectance and transmittance are the optical depths of the medium τ_x, τ_y, and τ_z, single scattering albedo Λ, and the scattering phase function depending on the parameter $\rho = 2\pi r/\lambda$, where r is the particle radius, and λ is the wavelength.

For different values of particle concentration in a disperse medium, the effects under study differ in magnitude, and ranges of their manifestation are determined by a specific set of the parameters.

As is well known, at some optical depths of disperse medium, the SBE starts to dominate over the interference and cooperative effects, and the last two cannot be investigated under such conditions. Therefore, transmittance measurements or calculations alone cannot be used to judge the character of interaction of radiation with the closely packed disperse medium.

Higher particle density is usually obtained by increasing concentration of scatterers, that is, for fixed geometrical parameters, by increasing the optical thicknesses of the medium to a level at which SBE vanishes, while the other two effects are manifested in the pure form.

The present paper is focused on the study of SBE to ascertain the limits of its manifestation in the process of radiation propagation through a medium with high concentration of scatterers.

A standard way of obtaining a densely packed media is through the scatterer deposition under the natural or artificial gravity. Such media are used for scientific researches and practical applications. Experiments on radiation passage through a medium with high volume concentration of scatterers are conducted in a cell of constant volume by varying the concentration of scatterers. In particular, in experiments with hydrosols contained in constant-volume cells, the concentration of scatterers was increased, as noted above, by their deposition. That way, the layer optical depth τ_x in the direction of radiation incidence remains roughly constant while the transverse optical depths increase in view of the fact that the increase of concentration occurs for constant geometric cross section of the cell.

The increase in transparency in this case may be caused by changes in the transverse optical depths. This effect is quantified in Fig. 1 showing the transmittance T of a layer of fixed optical depth $\tau_x = 20$ as a function of volume concentration of scatterers (curve *1*). Each value of volume concentration of scatterers is related to corresponding optical depth. Measurements were carried out in a cell with square cross section; used as a scattering medium was polystyrene latex with diffraction parameter $\rho = 2.8$. As our results show, there is strong dependence

0235-6880/95/12 1010-03 $02.00

of transmittance on the transverse optical depths due to the increase of multiple scattering contribution in the forward direction.

Along with the brightening effect, the layer reflectance R of densely packed media decreases with increasing density. Behavior of R for a spatially-bounded layer of a disperse medium is shown in Fig. 1 (curve *2*) plotted for the same parameter values as T. The increase in R is explained by the increase of multiple scattering contribution in the forward–backward direction.

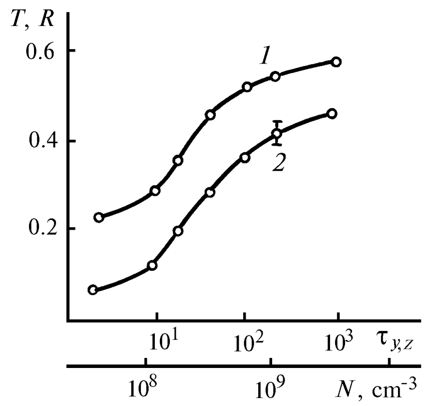

FIG. 1. Transmittance and reflectance of a medium as functions of its optical depths, with $\Lambda = 1$, $\tau_x = 20$, *and* $\rho = 2.8$. *Here N is the concentration of scatterers, curve 1 is for transmittance T, and curve 2 is for reflectance R.*

Our results can be used as criteria for manifestation of these brightening effects in the medium with densely packed scatterers. Individual contributions can be evaluated from simultaneous transmittance and reflectance measurements for the disperse layer of the medium. Once both T and R increase, the major contributor to the brightening effect is spatial boundedness of disperse medium.

Let us consider this effect in more detail by varying the optical parameters of disperse medium and radiation.

First let us examine transmittance T as a function of transverse optical depths τ_y and τ_z of a medium for spherical ($a = 1$) and anisotropic ($a = 12.09$) scattering phase functions (with a being the asymmetry factor). As calculations have shown, the transmittance changes by several orders of magnitude as the transverse optical depths of the medium change and depends on the depth τ_x in such a way that the region of T saturation shifts toward larger values of the transverse optical depths with the increase of τ_x.

If we now consider the ratio of T_2 (for anisotropic scattering phase function) to T_1 (for isotropic scattering phase function), we readily see (Fig. 2) that the dependence of transmittance on the shape of the scattering phase function is weak for small optical depths τ_x (curve *1*) while becoming stronger for larger τ_x not only for small (curve *2*) but also for large (curves *3*, *4*) $\tau_{y,z}$ values.

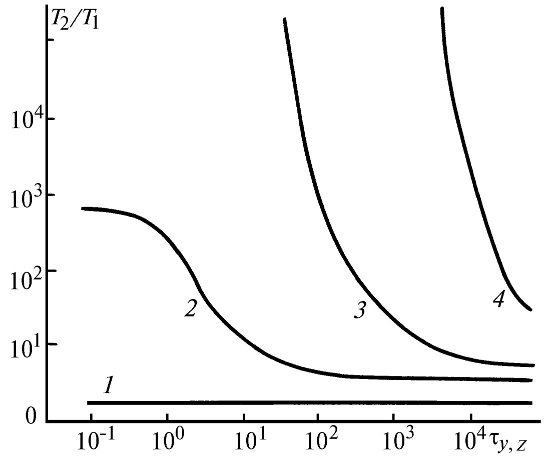

FIG. 2. Transmittance as a function of the shape of the scattering phase function: $\tau_x = 1$ *(1),* 10 *(2),* 10^2 *(3), and* 10^3 *(4).*

The dependence of reflectance R on the parameter a for constant τ_y, τ_z is shown in Fig. 3. From the figure we see that as a grows, the reflectance R decreases monotonically. The effect of the scattering phase function can be neglected for small transverse optical depths and $a > 2$ (curve *3*). As the transverse optical depths increase, the region of sensitivity to the effect of the scattering phase function shifts toward larger τ. To assess quantitatively the parameters at which the transmittance T of spatially bounded medium saturates, in analogy with Ref. 6 we define the parameter δ_T as

$$\delta_T = \frac{T_\infty - T(\tau_{y,z})}{T_\infty}\, 100\%, \qquad (1)$$

where T_∞ is the transmittance of a semi-infinite layer.

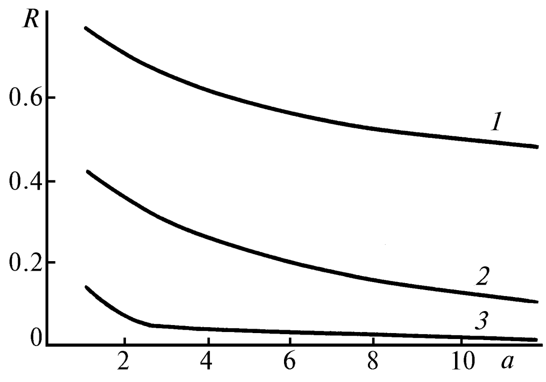

FIG. 3. Transmittance R as a function of the parameter a with $L = 1$ *and* $\tau_y = \tau_z = \tau_{y,z} = 10^2$ *(1),* 10 *(2), and* 1 *(3).*

Figure 4 shows the calculated relative error δ_T due to the neglect of spatial boundedness of a medium when radiation passes through it; the results are given as functions of the optical transverse depth, scattering phase function, and single scattering albedo. Shown are cases with $\Lambda = 1$ (curve *1*) and 0.9 (curve *2*). Calculations were done for isotropic ($a = 1$) and two anisotropic ($a = 6.66$ and 12.09) scattering phase functions at optical depth of the medium $\tau_x = 20$. From the figure we see that the error in determination of T decreases with increasing transverse optical depths of the medium as the degree of anisotropy of the scattering phase function becomes higher in the presence of absorption in the medium.

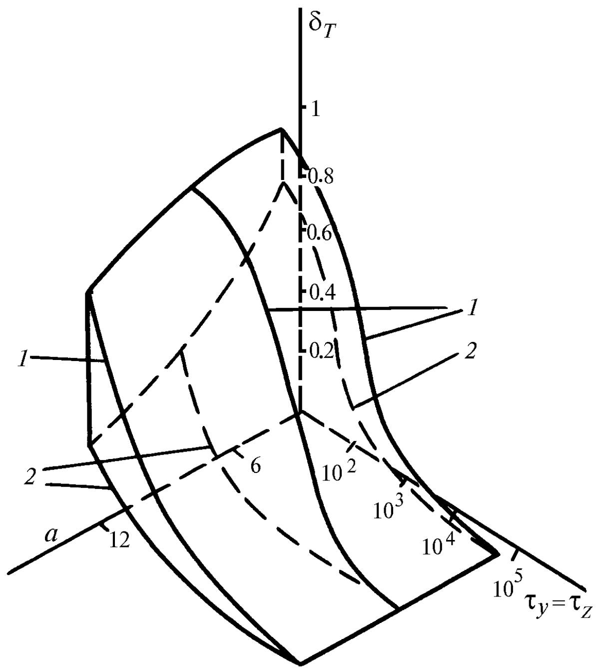

FIG. 4. Relative error in transmittance calculation due to the neglect of spatial boundedness of the medium with $\tau_x = 20$: $\Lambda = 1$ *(1) and* 0.9 *(2).*

The examined dependence of transmittance and reflectance allows us to assess the transverse optical depths of the medium at which it can be regarded infinite in the plane perpendicular to the direction of radiation propagation, taking into consideration the phase function asymmetry and single scattering albedo (Fig. 5, curves *1* and *2*). As the results indicate, the boundedness of medium can be neglected in the case of highly absorptive medium ($1 - \Lambda \geq 0.5$). However, in case of weak absorption ($1 - \Lambda \leq 0.05$), as the single scattering albedo changes from 1 to 0.97, for example, the minimum transverse optical depths of a medium with anisotropic scattering phase function decrease by two orders of magnitude, from 10^4 to 10^2. Decrease of the degree of the scattering phase function asymmetry also decreases minimum values of $\tau_{y,z}$, though to a lesser extent, e.g., as the asymmetry parameter a changes from 12.09 to 1 for conservative medium, the transverse optical depths at which T and R saturate change only by an order of magnitude, from 10^4 to 10^3.

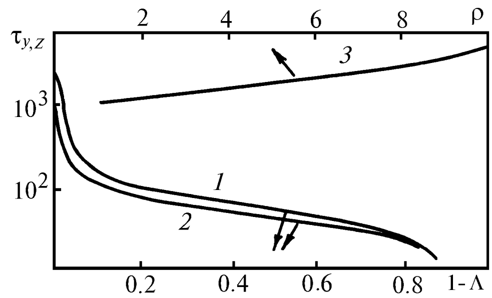

FIG. 5. Dependence of minimum transverse optical depths on single scattering albedo Λ *(curves 1 and 2) and parameter* ρ *(curve 3):* $a = 12.09$ *(1) and* 1 *(2).*

Using curve *3* of this figure, it is possible to estimate the minimum transverse optical depths as function of the scatterer size. As seen from the figure, as particle radii increase, the minimum transverse optical depths increase.

Summarizing, the results of this paper allow us to estimate the range of variation of the optical parameters of a disperse medium in which its spatial boundedness is significant. Beyond this range, major contributors to the brightening phenomenon are the interference and cooperative effects.

REFERENCES

1. A.P. Ivanov, V.A. Loiko, and V.P. Dik, *Radiation Propagation in Densely Packed Disperse Media* (Nauka i Tekhnika, Minsk, 1988), 199 pp.
2. V.G. Vereshchagin, in: *Radiation Propagation in Disperse Medium* (Minsk, 1982), pp. 135–152.
3. E.A. Vedernikova and M.V. Kabanov, Opt. Spectrosk. **13**, No. 1, 130–135 (1974).
4. D.H. Goedecke, J. Opt. Soc. Am. **67**, 1339–1348 (1977).
5. B.V. Goryachev, V.V. Larionov, S.B. Mogil'nitskii, et al., Opt. Spektrosk. **61**, No. 2, 423–424 (1986).
6. L.M. Romanova, Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **16**, No. 1, 40–48 (1980).