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A new method to retrieve spectral absorption coefficient of highly-scattering and weakly-absorbing materials

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ABSTRACT

A significant uncertainty in the absorption coefficient of highly scattering dispersed materials is typical in the spectral ranges of very weak absorption. The traditional way to identify the main absorption and scattering characteristics of semi-transparent materials is based on spectral measurements of normal-hemispherical reflectance and transmittance for the material sample. Unfortunately this way cannot be used in the case of *in vivo* measurements of optical properties of biological tissues. A method suggested in the present paper is based on thermal response to the periodic radiative heating of the open surface of a semi-transparent material. It is shown that the period of a variation of the surface temperature is sensitive to the value of an average absorption coefficient in the surface layer. As a result, the monochromatic external irradiation combined with the surface temperature measurements can be used to retrieve the spectral values of absorption coefficient. Possible application of this method to porous semi-transparent ceramics is considered. An example problem is also solved to illustrate the applicability of this method to human skin. The approach suggested enables one to estimate an average absorption coefficient of human skin of a patient just before the thermal processing.

1. Introduction

A review of experimental methods and identification procedures for optical properties of disperse media is available in [1]. Determination of the complete set of these properties, namely, absorption and scattering coefficients and scattering phase function requires bi-directional intensity measurements with fine angular resolution and application of sophisticated identification techniques. A simpler and computationally more efficient approach involves using directional-hemispherical transmittance and reflectance [2–5], often coupled with the transport approximation [3,6]. The transport approximation reduces the set of optical properties to be determined to the absorption and transport scattering coefficients. It has been shown that absorption coefficient and transport scattering coefficient are sufficient for engineering heat transfer analysis [3].

Unfortunately, traditional methods are sometimes not applicable because of very low transmittance of highly scattering samples. One of the known examples in the case of porous ceria ceramics when a relatively complex combined approach was suggested to retrieve both the absorption coefficient and transport scattering coefficient of this material in the spectral range of especially weak absorption [7,8]. There are also some other situations when the measurements of transmittance cannot be made. The known example is *in-situ* measurement of optical properties of living biological tissues [9]. In both cases, one needs an alternative approach to retrieve the spectral absorption coefficient of semi-transparent media.

The method suggested in the present paper to retrieve the absorption coefficient is based on solution for the combined radiative-conductive problem at periodic irradiation of the material under investigation. The resulting

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Nomenclature

c	specific heat capacity
d	thickness of sample
D	radiation diffusion coefficient
E	function introduced by Eq. (3)
G	function introduced by Eq. (4a)
h	heat transfer coefficient
I	radiation intensity
J	diffuse radiation intensity
k	thermal conductivity
q	radiative flux
$\vec{r}$	spatial coordinate
R	reflectance
t, Δt	time interval
T	temperature
W	absorbed power
z	normal coordinate

Greek symbols

α	absorption coefficient
β	extinction coefficient
θ	angle measured from the normal
λ	radiation wavelength
μ	cosine of an angle
$\overline{\mu}$	asymmetry factor of scattering
ρ	density
σ	scattering coefficient
τ	optical thickness
ξ	eigenvalue determined by Eq. (7)
ω	scattering albedo

Subscripts and superscripts

0	initial
1, 2	side number
e	external
min	minimum
max	maximum
n-h	normal-hemispherical
tr	transport
λ	spectral

periodic variation of the hot surface temperature depends on the penetration depth of the monochromatic incident radiation which leads to the material heating. The surface temperature can be measured to determine the period of these temperature variations as it was done in paper [10]. Note that exact values of temperature are usually not important because the effect of a systematic error in temperature on the period of temperature oscillations due to periodic irradiation is relatively small. It should be recalled that it is insufficient to know the temperature at the irradiated surface. On the contrary, it is important to know the transient temperature profiles in the material layer. A computational study of these profiles is impossible without the data for volumetric optical properties of the material under consideration.

This period, Δt, depends on many parameters of the problem. At the same time, some of these parameters can be determined independently. Particularly, the medium scattering albedo can be estimated using the spectral measurements of reflectance of optically thick samples. It is also important that a special thermal regime of laboratory experiments can be chosen to minimize the effect of natural uncertainty of the heat transfer parameters on the value of Δt. As a result, the measured period of quasi-steady surface temperature variations can be used to identify the spectral absorption coefficient $\alpha_\lambda$of the material.

The computational model presented in the paper enables one to obtain a dependence of $\Delta t(\alpha_\lambda)$ which is monotonic and sufficiently strong for the reliable identification of α_λ in some important practical problems. Possible application of the method developed to weakly absorbing but highly scattering porous ceramics and to human skin, which is characterized by a significant uncertainty in spectral absorption coefficient in the so-called therapeutic window, is illustrated below by using numerical solutions for two example problems.

2. Radiative transfer problem

A one-dimensional (1-D) radiative transfer problem is considered. The external monochromatic radiation illuminates uniformly a plane-parallel layer of an isotropic and homogeneous material along the normal. Following [3,6] we use the transport approximation for the scattering phase function to simplify significantly the scalar radiative transfer equation (RTE). After integration over an azimuth angle, the RTE and the boundary conditions for the optically thick layer can be written as follows [3] (subscript λ is hereafter omitted for brevity):

$$\mu\frac{\partial \bar{I}}{\partial z}+\beta_{\rm tr}\bar{I}=\frac{\sigma_{\rm tr}}{2}\int_{-1}^{1}\bar{I}(z,\mu)d\mu \quad \mu=\cos\theta \quad z>0 \tag{1}$$

$$\bar{I}(0,\mu)=\delta(1-\mu) \quad \bar{I}(\infty,-\mu)=0 \quad \mu>0 \tag{2}$$

where $\bar{I}(z,\mu)=I(z,\mu)/q_{\rm e}$ is the normalized (per unit incident radiative flux) spectral radiation intensity at point $\vec{r}$ in direction μ, $\sigma_{\rm tr}=\sigma\cdot(1-\overline{\mu})$ is the transport scattering coefficient (σ is the ordinary scattering coefficient, $\overline{\mu}$ is the asymmetry factor of scattering), $\beta_{\rm tr}=\alpha+\sigma_{\rm tr}$ is the spectral transport extinction coefficient, α is the spectral absorption coefficient. Note that transport approximation is widely used in radiative transfer calculations during many years. It was confirmed that hemispherical characteristics of radiation field in scattering materials characterized by multiple scattering are well described using this approximation. The first of boundary conditions (2) is written for the simplest case of a nonrefracting medium. Fortunately, the latter