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The effect of BRDF surface on radiative transfer within a two-dimensional graded index medium

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ABSTRACT

The traditional diffuse or specular surface assumption is insufficient to accurately characterize the reflection characteristics of a practical surface under some circumstances, which could cause distinct deviation in radiative heat transfer analysis and temperature measurements. The anisotropic reflection of a real surface can be well featured by the Bidirectional Reflectance Distribution Function (BRDF). This study aims to solve the radiative heat transfer in a two-dimensional non-uniform refractive index and anisotropic scattering medium coupled with the BRDF surface. The Distribution of Ratios of Energy Scattered by the medium Or Reflected by the boundary surface (DRESOR) method is extended to deal with this issue. The effect of BRDF surface on the radiative heat flux and radiative intensity is investigated varying with optical thickness and scattering albedo of medium by compared to the corresponding diffuse surface. It is found that the more deviation from the diffuse characteristics the BRDF surface has, the larger difference of the radiative heat flux and intensity between the BRDF and diffuse surface there exits. The increased optical thickness and scattering albedo both decrease the difference of radiative flux on the wall between the BRDF and corresponding diffuse surface. And the influence of the reflection of the BRDF boundaries can be alleviated with thick optical thickness or large scattering capacity in the medium. The results demonstrate that the BRDF surface can impose remarkable impact on the radiative heat transfer, and an appropriate BRDF model should be introduced to be coupled with radiative transfer procedure in the accurate analysis of multi-dimensional radiative transfer problem if the boundary possesses the anisotropic reflection properties.

1. Introduction

For the radiative transfer in a two-dimensional medium with graded index, rays propagating inside the medium are not straight lines determined by the Fermat principle [1]. Although the radiative transfer in a two-dimensional gradient index medium is more difficult, many methods have been developed to solve the problem of radiative heat transfer in a multi-dimensional geometric region, for example, finite volume method (FVM) [2], Galerkin finite element method (GFEM) [3], Monte Carlo (MC) method [4], ray emission model (REM^2) method [5], discrete ordinates method (DOM) [6], natural element method (NEM) [7], Lattice Boltzmann model (LBM) method [8], Petrov-Galerkin meshless method [9] and so on. However, in the most of the researches mentioned above, boundary surfaces are assumed to be blackbody or diffuse. In fact, the feature of the practical boundary surface is very complicated, which is determined by many factors, such as material, roughness, temperature and so on [10,11]. This specialized assumption of blackbody or diffuse boundary may cause some deviations or even errors in the radiative heat transfer analysis and temperature measurements. The diffuse surface assumption can cause large radiation analysis errors in some conditions and the deviation may be up to 100 Celsius during the temperature measurement [12]. Therefore, a comprehend understanding of the directional radiative properties and the measurement of the directional reflectance distribution of the surface are essential to decrease the reflection error. The Bidirectional Reflectance Distribution Function (BRDF) [13], which describes the interrelation between the incident and outgoing radiation, is considered as a more rigorous approach to represent a real surface. The BRDF research has significant potential applications in many areas through the years, such as remote sensing telemetry [14], computer graphics [15], image recognition [16] and so on. Recently, using DRESOR method to solve radiative heat transfer problems within a one-dimensional graded index medium coupled with BRDF surfaces has been reported [17]. Chai et al. [18,19] has dealt with the transient radiative heat transfer

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Nomenclature

A_i	surface element i
f_r	BRDF (Bidirectional Reflectance Distribution Function)
E	the evaluation function
E_0	the original energy of each ray
I	radiative intensity, W/(m^2·sr)
k	a parameter of the Minnaert model
n	refractive index
N_u	number of energy bundles emitted from a volume or surface element
q_w	net radiative heat flux at wall, W/m^2
R	random number
R_d^s	R_d^s DRESOR value, 1/m^3, or 1/m^2
$\mathbf{s}$	directional vector
S	radiative source function, W/(m^2·sr)
T_g	medium temperature
T_w	wall temperature
V_i	volume element *i*

Greek letters

β	extinction coefficient, 1/m
σ_s	scattering coefficient, 1/m
ε	emissivity of the surface
θ	zenith angle, rad
κ	absorption coefficient, 1/m
ρ	reflectivity of the surface
τ_H	optical thickness of square enclosure
φ	azimuth angle, rad
Φ	scattering phase function
ω	scattering albedo
Ω	solid angle

Subscripts

b	blackbody
i	incident
r	reflected
w	surface or wall

problems coupled with the BRDF surfaces by the DRESOR method and investigated the double-layer coating pigmented with CuO particles of different concentrations on aesthetic and thermal aspects. Nevertheless, it should be noted that the researches are designed to handle one-dimensional radiative heat transfer problems rather than multi-dimensional ones.

Due to the difficulties of measuring comprehensive values of the BRDF by experiments for materials in different conditions, there exists a pervasive need for the BRDF mathematical modeling. There are three main kinds of models by now: the theoretical model, the geometry optical model and the semi-empirical/empirical model [20]. Note that some semi-empirical/empirical models proposed by Torrance and Sparrow [21], Minnaert [22], Phong [23], Thomas [24], Renhorn and Boreman [25] and so on, have been widely applied due to having advantages in getting more information about the BRDF surface.

In the present study, the Minnaert model suitable for many practical industrial walls or surfaces is applied to model the BRDF surface, and the DRESOR method is extended to solve two-dimensional radiative transfer in a graded index medium coupled with BRDF surfaces. Compared with the corresponding diffuse reflection surface, the effects of optical thickness, scattering albedo and different BRDF surfaces on radiation heat transfer in the graded index medium will be investigated.

2. Principles

2.1. The DRESOR method for solving the RTE coupled with the BRDF surface

The integral radiative transfer equation (RTE) in an absorbing, emitting and anisotropic scattering medium with graded index can be described as [26].

$$\frac{I(r,\mathbf{s})}{n_r^2} = \frac{I_w(r_w,\mathbf{s}_w)}{n_w^2}\exp\left(-\int_{s_w}^{s}\beta ds''\right) + \int_{s_w}^{s} S(r',\mathbf{s}')\exp\left(-\int_{s''}^{s}\beta ds'''\right)\beta ds'', \quad (1)$$

where the source function $S(r',\mathbf{s}')$ can be expressed as follow

$$S(r',\mathbf{s}') = (1-\omega)I_b(r') + \frac{\omega}{4\pi}\int_{4\pi}\frac{1}{n_{r'}^2}I(r',\mathbf{s}_\mathrm{i})\Phi(\mathbf{s}_\mathrm{i},\mathbf{s}')d\Omega_i, \quad (2)$$

where the boundary condition of the non-transparent surface is [27]

$$I_w(r_w,\mathbf{s}) = n_w^2\varepsilon(r_w)I_b(r_w) + \frac{1}{\pi}\int_{\mathbf{n}\cdot\mathbf{s}'<0}\rho''(r_w,\mathbf{s}',\mathbf{s})I(r_w,\mathbf{s}')|n\cdot\mathbf{s}'|d\Omega'. \quad (3)$$

Introducing the DRESOR method, the radiative intensity $I(r,\mathbf{s})$ expression by the DRESOR method can be obtained as follow

$$\begin{aligned}\frac{I(r,\mathbf{s})}{n_r^2} = {} & \frac{1}{n_w^2}\left(\frac{n_w^2}{\pi}\right)\Bigg\{[\pi\varepsilon'(r_w,\mathbf{s}')I_b(r_w)] + \int_W \frac{n_{w'}^2}{n_w^2}R_d^s\left(r_w',r_w,\mathbf{s}'\right) \\ & \times\left[\pi\varepsilon\left(r_w'\right)I_b\left(r_w'\right)\right]dA' + \int_V \frac{n_{r''}^2}{n_w^2}R_d^s\left(r'',r_w,\mathbf{s}'\right) \\ & \times\left[4\pi\beta(1-\omega)I_b\left(r''\right)\right]dV''\Bigg\}\cdot\exp\left[-\int_{s_w}^{s}\beta ds''\right] \\ & + \int_{s_w}^{s}\frac{1}{4\pi\beta}\Bigg\{4\pi\beta(1-\omega)I_b(r') + \int_W \frac{1}{n_{r'}^2}R_d^s\left(r_w',r',\mathbf{s}''\right) \\ & \times\left[\pi\varepsilon\left(r_w'\right)n_{w'}^2 I_b\left(r_w'\right)\right]dA' + \int_V \frac{1}{n_{r'}^2}R_d^s\left(r'',r',\mathbf{s}''\right) \\ & \times\left[4\pi\beta(1-\omega)n_{r''}^2 I_b\left(r''\right)\right]dV''\Bigg\}\cdot\exp\left[-\int_{s'}^{s}\beta ds''\right]\beta ds',\end{aligned} \quad (4)$$

where $\varepsilon(\mathrm{r}) = \frac{1}{\pi}\int_{2\pi}\varepsilon'(\mathrm{r},\theta_i,\varphi_i)\cos\theta_i d\Omega_i$ is the hemispherical emissivity, $\beta = \kappa + \sigma_s$ is the extinction coefficient. In order to avoid duplication, the details of derivations can be referred to the literature [28]. The DRESOR values, $R_d^s(r_w',r_w,\mathbf{s}')$, $R_d^s(r'',r_w',\mathbf{s}')$, $R_d^s(r'',r',\mathbf{s}'')$