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Inverse identification of radiative properties of a multi-component media in MPA modeling of radiative transfer☆

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ABSTRACT

Inverse identification of the radiative properties of a two-component media based on multi-phase approach (MPA) formulation of the radiative transfer phenomenon is investigated. Packed bed of semitransparent spheres under a normal collimated laser beam is considered as the geometry of the mentioned problem. Discrete normal directional reflectance and transmittance of the packed bed is used as input data to the identification procedure. The sensitivity of these two parameters to radiative properties of the medium is studied first, followed by the inverse parameter estimation. The discrete ordinates method is used to solve the direct problem while interior trust region (ITRA) algorithm is utilized in the identification process. Results indicate the ability of the presented procedure to estimate the desired radiative properties of the medium within an acceptable error margin. Moreover, the effect of uncertainty of the normal directional reflectance and transmittance data on the accuracy of the estimated parameters is assessed.

1. Introduction

Thermal radiation is usually the main mode of heat transfer in high temperature applications such as chemical reactions in packed bed, solar collectors, furnace design, laser radiations, sintering, porous burners and heat exchangers [1–8]. Analysis of radiation in a multi-component non-homogeneous media is more complicated than that of a homogeneous media.

In general, methods that simulate radiative heat transfer in multi-component media are broadly classified into two groups: 1) models in continuum scale and 2) models in discrete scale [9]. In continuum scale, modeling is based on two different approaches: a) homogenous phase approach (HPA), which has been studied and used by many researchers and b) multi-phase approach (MPA) which is the most recent scheme and it is not well-studied yet to the best knowledge of the authors. This approach leads to vector RTE equations.

Zeghondy et al. [10] attributed a separate intensity field, and therefore a separate RTE, to each component of a multi-component media. They introduced the multi-phase approach to deal with the radiation in such media. Gusarov [11,12] considered a medium of uniformly distributed isotropic monosized spheres to simulate the radiation in porous media. For such a medium, he used logical simplifications in conservation laws to express all radiative properties involved in vector RTE at each point as functions of local radiative properties. Limited number of works focused on performance analysis of MPA and compared it to other available approaches [1,13–17].

The biggest challenge in MPA is assigning appropriate radiative properties to each component. Using spatial averaging theory, Lipinski et al. [9] presented a set of accurate equations for estimating the radiative properties. However, these equations require tedious calculations in the discrete scale. Basically, there are two ways to estimate the radiative properties, or more generally the thermo physical properties, of a multi-component medium:

- Microscopic methods that analyze the structure of the medium in a microscopic scale before applying the appropriate models;
- Macroscopic methods that use the inverse parameter estimation techniques using experimental data.

One of the recent approaches to find radiative properties is the use of the direct simulation in the discrete scale, as in Radiative Distribution Function Identification (RDFI), and direct calculation of the properties according to their definitions. Implementation of this approach requires the morphological information of the medium as well as the local radiative properties of each component. It can be said that this approach is based on the statistical formulation of the physical laws of radiation [10,18]. One of the advantages of this approach is obviating the dependency on the radiative models that are used in an equivalent homogenous medium. Tancrez and Taine [19] used this approach to achieve extinction,

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Nomenclature

A	specific surface of the medium
E	relative uncertainty
f	volumetric fraction
F	objective function
I	radiation intensity
m	refraction index ratio
N	number of directions
P	specularity parameter
Q_i	incident energy flux
r_β	extinction ratio
$R(\theta)$	normal-directional reflectance
S	normalized sensitivity
$T(\theta)$	normal-directional transmittance
$\overrightarrow{x}$	vector of estimation parameters
z	distance/coordinate

Greek

α	internal absorption coefficient
β	extinction coefficient
γ	radiation direction polar angle
Δ	Dirac's delta function
θ	reflected radiation direction polar angle
λ, λ'	angles of reflection and refraction
μ	direction cosine
ρ	diffuse reflectivity
ρ'	specular reflectivity
σ	standard deviation of noise
τ	optical thickness
τ_L	optical thickness of the medium
Φ	scattering phase function
χ, χ'	angles of incidence and refraction
ω	albedo parameter

Subscripts

0, 1	number of component
cr	critical
e	experimental
i	inside
o	outside
t	theoretic

Superscripts

0	top surface
c	collimated
k	iteration number
R	reflectance
s	scattered
T	transmittance
↑	upward
↓	downward
-	average

absorption and scattering coefficients as well as scattering phase function in some special cases of multi-phase media and Zeghondy et al. [10] extended it to more general cases.

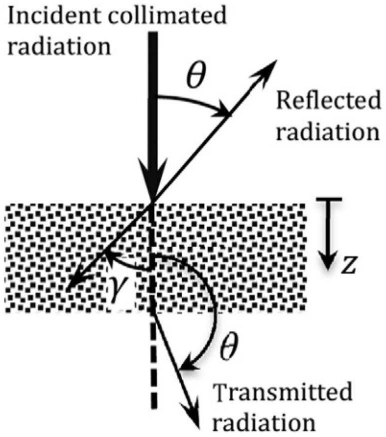

Fig. 1. Schematic geometry of problem and the frame of reference.

Another approach for finding radiative properties of a multi-phase medium is modeling its representative geometrical structure. In this approach, a representative geometric model is presented based on the morphological analysis of the structure. Then, thermal properties are estimated using the electromagnetic and heat transfer theories for this model. By employing logical assumptions and appropriate methods, these estimations are extended to the entire multi-phase medium [20–23].

Direct simulation in discrete scale along with the inverse parameter identification is considered as another effective approach to assess the radiative properties. In this approach, simulation is done using the Monte Carlo (MC) method. Reflectance and transmittance coefficients as well as intensity field of the medium are determined. These results are then compared to the same results obtained by an equivalent semi-transparent medium (i.e. homogenous phase approach). This comparison aids the estimation of spectral radiative properties by the inverse techniques [24–26]. Applying Monte-Carlo in discrete scale generates large amount of information about the radiation in a multi-component medium. Moreover, based on the results of Monte-Carlo method, a criterion can be defined to determine the validity of approximating a multi-component medium with its equivalent homogenous medium. It also results in valuable information about the physical aspects of radiation heat transfer that can be applied in designing the new experimental schemes [19]. On the other hand, using Monte-Carlo requires accurate information regarding properties of solid and liquid phases as well as geometric structure of the multi-component media. This causes Monte-Carlo to be relatively an expensive methodology.

In contrast to the abovementioned microscopic approaches, one of the macroscopic approaches to find the radiative properties of a medium is to use the experimental data along with inverse parameter estimation techniques. The radiative properties of an equivalent medium (in homogeneous phase approach) such as extinction coefficient, scattering albedo and phase function parameters are estimated based on the comparison of the mathematical model and experimental data. As

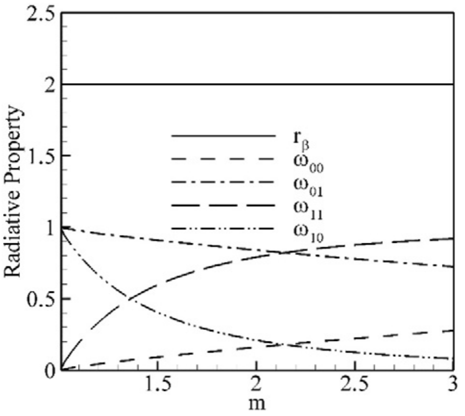

Fig. 2. Scattering albedos and extinction ratio as a function of m for $f_0 = 0.5$.