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Inverse boundary design radiation problem with radiative equilibrium in combustion enclosures with PSO algorithm☆

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ABSTRACT

An inverse analysis is employed to estimate the unknown heat flux distribution over the heater surface of two dimensional enclosures with regular and irregular geometries filled by non-gray participating media, from the knowledge of desired temperature and heat flux distributions over the given design surface. The medium is in radiative equilibrium. The radiative transfer equation is solved by the modified discrete ordinates method combined with two models for simulation of non-gray media. The inverse solutions are compared by using two approaches; the conjugate gradient method (CGM) and the particle swarm optimization (PSO) algorithm. The PSO algorithm shows accurate and reliable results in regular geometry with high optical thickness.

1. Introduction

Inverse radiation heat transfer problems have attracted intensive efforts in the field of thermal sciences in the past years. More recently, the inverse design problems have been attracting interest, especially in the field of radiative heat transfer or combined modes with radiation. Inverse design problems are classified as inverse boundary design, inverse heat source design, and inverse shape design problems [1–16]. Irregular geometries may be modeled with a boundary-fitted grid. However, it is suitable to formulate a solution procedure to model the irregular geometries using Cartesian coordinate system in order to avoid additional complications arising from the irregular boundary-fitted computational grids. Amiri et al. [17,18] have used a new form of the blocked-off method in which three blocked-off variables have been defined, instead of introducing an additional source term for each control volume. Best solution by simulation of the movement and the flocking of birds can be obtained by particle swarm optimization. Particle swarm optimization is a type of global algorithm to searching of best solution. Firstly, it was introduced in 1995 by Eberhart and Kennedy [19]. The algorithm works by initializing a flock of birds randomly over the searching space. It has been studied extensively by many researchers and becomes one of the best global optimization algorithms in recent years [20–25].

The objective of this work is to solve the inverse design problem in regular and irregular geometries with non-gray media in radiative equilibrium. The blocked-off method based on the work by Amiri et al. [17] is used to solve the radiative transfer equation (RTE) in irregular geometries. Recently Payan et al. [26] solved inverse boundary design problem in non-gray medium with a specific temperature distribution. They show that the CGM is an appropriate method for inverse boundary design in non-gray media with specified temperature distribution. However, for the case of radiative equilibrium, temperature distribution in the medium, and hence, the weight coefficients are unknown. However, temperature distribution is appeared in inverse problem. The unknown temperature distribution and weight coefficients cause the inverse problem to be very non-linear and then very dependent to initial guess. In this paper, two models are used to simulate the spectral dependence of the absorption coefficient, and the results obtained by different models and algorithms are compared.

2. Description of problem

Fig. 1 shows a two-dimensional irregular enclosure. The enclosure contains a non-gray participating medium, whose absorption coefficient is dependent on the wavelength. All the walls are diffuse-gray emitter and absorber. The homogenous gases are at radiative equilibrium in the medium. The aim of the inverse problem is to find the heat flux distribution over the heater surface in such a way that both desired thermal conditions (temperature and heat flux) over the design surface are simultaneously satisfied. This problem could be imagined as a simplified model in the design of real systems with non-gray gases. The uniform temperature and heat flux distributions are imposed over the design surface. The remaining surfaces, except the heater surface, are adiabatic. No boundary condition is known over the heater surface.

The spectral radiative transfer equation (SRTE) in a non-scattering medium with diffuse-gray walls is written by a discrete set of M coupled

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Nomenclature

A	area, m^2
a	weighting coefficient
C	absorption cross-section, m^2/mol
C_1	cognitive coefficient
C_2	social coefficient
D	molar density, mol/m^3
d	direction of descent
F	blocked-off variable
G	objective function
I	radiation intensity, W/m^2 sr
J	sensitivity coefficient
K	absorption coefficient per total pressure (1/(m atm))
L_{mb}	mean beam length
M	number of directions
N	number of gray gases
$\vec{n}$	normal direction
P	gas pressure
$\mathbf{P}_i(t)$	best position of particle i at iteration t
$\mathbf{P}_g(t)$	best position of all particle at iteration t
q	heat flux, W/m^2
R	number of grids over the design surface
$\vec{r}$	position vector
r_1, r_2	random numbers
S_r	radiation source term, W/m^3
S	number of grids over the heater surface grid
$\vec{s}$	unit vector into a given direction
T	temperature, K
$\forall$	volume of control volume
$\mathbf{V}_i(t)$	velocity of i-th particle
W	quadrature weights
x, y	Cartesian coordinates
$\mathbf{X}_i(t)$	position of i-th particle
Y	molar fraction

Greek letters

β	step size
ε	emissivity
κ	absorption coefficient, 1/m
γ	peripheral length
ξ, μ	direction cosines
σ	Stefan–Boltzmann constant (5.67×10^{-8}W/m^2 K^4)
ω	inertia weight
Ω	solid angle, sr

Subscripts

b	blackbody
d	design-desired
e	estimated
G	gas
h	heater
Max	maximum value
Min	minimum value
New	new value
Old	old value
n, p	gray gas number
R	node on design surface element
S	node on heater surface
$Start$	starting value
End	ending value
W	wall
	wave number

Superscripts

k	iteration number
m	direction
$+, -$	outgoing and incident

differential equations for a finite number of directions $\vec{s}^m$. Integrals over solid angels are replaced by a quadrature of order m yielding:

$$\frac{dI_\eta\left(\vec{r}, \vec{s}^m\right)}{ds} = -\kappa_\eta I_\eta\left(\vec{r}, \vec{s}^m\right) + \kappa_\eta I_{b\eta}\left(\vec{r}\right), \quad m = 1, \ldots, M \tag{1}$$

and the boundary conditions are given by:

$$I\left(\vec{r}_w, \vec{s}^m\right) = \varepsilon_w I_{b\eta}\left(\vec{r}_w\right) + \frac{(1-\varepsilon_w)}{\pi} \sum_{m=1}^{M} I_\eta\left(\vec{r}_w, \vec{s}^m\right) W^m, \quad n_w \cdot s^m > 0. \tag{2}$$

In order to solve Eq. (1) with boundary condition as presented in Eq. (2), the radiative heat transfer calculations must be carried out at each wave number, η, of the spectrum followed by an integration over all wave numbers to obtain the total heat transfer rates. However, such an approach requires a great deal of effort and time, since the spectral range involves many thousands of spectral lines. The non-gray medium may be replaced by a gray gaseous medium with a constant absorption coefficient at average temperature. However, more accurate approach is to replace the integration of spectral properties with a summation over a set of gray gases to simulate the properties of the non-gray medium. Summaries of models to simulate the non-gray behavior of gaseous media are presented in the next section.

3. Models for simulation of non-gray gaseous media

3.1. The gray model

In this model the non-gray gas is replaced by a gray gas with a constant absorption coefficient given by:

$$\kappa = -\ln(1-\varepsilon_{tot})/L_{mb} \tag{3}$$

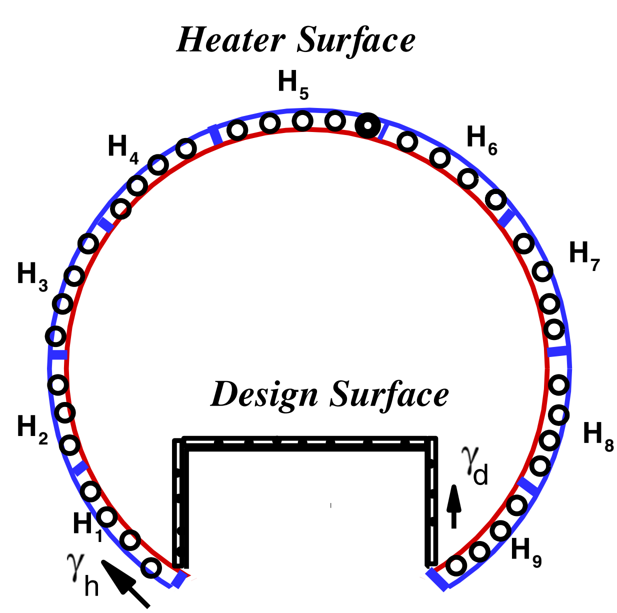

Fig. 1. The schematic shape of the radiant enclosure and locations of design and heater surfaces.