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Finite volume method for non-equilibrium radiative heat transfer

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ABSTRACT

Radiative heat transfer is an important physical phenomenon, especially in the high speed and high temperature flow regimes, making its application important in space exploration vehicles. This paper presents the development and validation of computational tools for modeling the radiative heat transfer that can be either employed by itself or coupled with a computational fluid dynamics solver to analyze aerothermodynamics environments. A generalized mesh is used for discretization of the spatial domain and a finite volume method is used for solving the radiative heat transfer equation. Solution of the radiative heat transfer equation in an angular domain is carried out in a parallel environment. This numerical approach is validated with different benchmark test cases for gray gas radiation in various geometries. To enable the simulation of non-gray gas radiation, the full spectrum correlated-k model is implemented into the radiation solver. A grid sensitivity study is conducted to analyze the dependency of mesh resolution in spatial and angular domains on solution accuracy. The results of the validation studies, grid sensitivity studies, and parallel performance of the implementation are presented in this paper.

1. Introduction

Radiation is an important mode of heat transfer which has a wide range of applications from combustion to aerodynamic heating of atmospheric re-entry vehicles. For example, in the Apollo mission, it was found that 30% of the total heat transfer rate during re-entry was due to radiation from the shock layer [1]. In re-entry applications, due to the high velocity of the re-entry vehicle, a detached bow shock is formed in front of the vehicle. This shock layer energizes the gas around the windward blunt surface of the re-entry vehicle and causes very high temperatures in this region, which is in a state of thermo-chemical non-equilibrium. The high temperature gas produces large radiation because the radiative heat transfer is a function of the fourth power of the temperature. Hence, at high temperatures, radiation becomes more important than conduction and convection. Combinations of large radiative and convective heat fluxes contribute to large heat loads on the surfaces of the re-entry vehicle. A Thermal Protection System (TPS) is often employed to protect the surface of re-entry vehicles from such severe aerodynamic heating. An inadequate or inappropriate choice of TPS material might result in the failure of TPS, whereas excessive insulation results in the addition of unnecessary weight to the vehicle. To determine the proper amount of TPS material, it is critical to have a reliable, accurate estimation of the radiative and convective heat transfer based on the flight trajectory and condition of the mission. The experimental study of the application, using either ground or flight tests of this type is very expensive, or in some cases impractical and often not available. Numerical modeling and simulations of radiation provide a low-cost, viable approach to evaluate the radiative heat loads associated with such a scenario. However, numerical simulations of radiative heat transfer encounter several technical challenges: (1) computational efficiency vs. numerical accuracy, and (2) evaluation of radiative properties. These technical difficulties will be detailed in the following literature review section. The objectives of this study are to:

i. develop a numerical solver that can efficiently predict the radiative heat transfer and can be easily used in combination with computational fluid dynamics (CFD) solvers for simulating aerodynamic heating,
ii. investigate numerical approaches for evaluating the radiation intensity in solving radiative transfer equation (RTE), and
iii. explore numerical models for estimating the radiative properties of a gray-gas medium.

In this study, several benchmark test cases are also employed to validate and verify the developed radiation solver, and the results are reported herein.

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Nomenclature

a	parameter for the steepness or non-uniformity of the temperature profile
d	distance
e	control surface on the east side of the reference cell
f	fractional Planck function
g	equivalent Planck function
g_{ref}	reference equivalent Planck function
h	non-dimensional parameter defined in Eq. (11)
I	intensity of radiation
I_b	black body intensity
$I_{b\eta}$	blackbody intensity at wave number, η
I_g	intensity at equivalent Planck function, g
$I_{l,f}$	intensity associated with the direction, l at the control surface
$I_{l,P}$	intensity at the control volume in the direction, l in the cell P
$I_{l,e}$, $I_{l,w}$, $I_{l,n}$, $I_{l,s}$	intensities associated with the direction, l corresponding to east, west, north, and south faces of a spatial mesh, respectively
J_f	geometric factor
k	absorption coefficient
k_η	absorption coefficient at wave number, η
l	discrete outgoing ray direction vector at a given point
l'	discrete incoming ray direction vector at a given point
L	length of the domain
M	number of control angles
np	number of processors
N_θ	number of control angle divisions in polar direction
N_ϕ	number of control angle divisions in azimuthal direction
n	control surface on the north side of the reference cell
p	partial pressure of species
P	reference cell
Q	dimensional heat transfer rate
q	non-dimensionalized radiative heat flux
q''	heat flux at the wall
$\vec{r}$	position vector
s	coordinate along the ray or control surface on the south side of the reference cell
$\vec{s}$	outgoing ray direction vector at a given point
$\vec{s}'$	incoming ray direction vector at a given point
S	source term or control volume on the south side of the reference cell
S_m	modified source term
t_{np}	CPU time taken for a simulation using np processors
t_s	CPU time taken for a simulation using one processors
T	temperature
T_0	peak temperature
T_c	temperature at the mid-point between the plates
T_m	medium temperature
T_{ref}	reference temperature
T_w	wall temperature
x	species mole fraction
x, y, z	Cartesian coordinates
u	scaling function
w	control surface on the west side of the reference cell
W	control volume on the west side of the reference cell
ΔV_0	volume of the control volume
β_m	modified extinction coefficient
θ	polar angle subtended by the centroid of the solid control angle
κ	raw absorption coefficient
κ_η	raw absorption coefficient at wave number, η
σ	Stefan–Boltzmann constant
σ_s	scattering coefficient
η	wave number
ϕ	scattering phase function
Ω	control angle corresponding to outgoing ray direction
Ω'	control angle corresponding to incoming ray direction
$\Omega^{l'l}$	average scattering phase function from a control angle l' to control angle l
φ	azimuthal angle subtended by the centroid of the solid control angle
ω_l	solid angle corresponds to direction l

2. Literature review

Numerical simulation of radiative heat transfer in general involves two major steps. The first step involves the evaluation of radiative properties by analyzing the spectrum of the participating medium for a set of given conditions, such as temperature, pressure, composition of participating media, and particulates. The second step is to compute the radiative heat transfer using the estimated radiative properties from the first step. Various models available to obtain spectral radiative properties as well as different numerical approaches to compute the radiative heat transfer are reviewed and summarized here.

2.1. Numerical approaches to predict the radiative heat transfer

The use of numerical methods to compute radiative heat transfer has received substantial amount of attention in the past decades. Among them, five numerical methods (and their variations) have become more popular than the others: Zone method [1], Monte Carlo method [2], spherical harmonics methods (approximate P_N methods) [3], discrete ordinates method (DOM) [4], and finite volume method (FVM) [5].

The zonal method, originally developed by Hottel and Cohen [1], is an effective and rigorous approach for estimating radiative heat transfer in a semitransparent media. In this method, the domain of interest (usually an enclosure) is divided into a finite number of isothermal surface areas or volume zones. The radiative heat transfer rate is determined by the emissive power and the mutual direct exchange areas (DEA) of each zone in the enclosure. The DEA represents the geometrical and optical relationship of every zone with each other. A detailed description of the zonal method can be found in Ref. [6]. Evaluation of the DEA is the basis of the zonal method and it involves the calculation of four, five, and six-dimensional integrals. The integrands have strong singularities when two zones are adjacent, or overlap each other (self-irradiation). High accuracy numerical solution of these multi-dimensional integrals is difficult to achieve [7]. The zone method is very accurate and can easily be adopted for problems involving scattering. However, the use of the zone method can be computationally expensive. In addition, to simulate the radiation effect and aerothermodynamics in a coupling manner, this method is not compatible with computational fluid dynamics (CFD) approaches.

The Monte Carlo method is a numerical method based on a statistical approach, which is particularly helpful in calculating radiation since the deterministic approach complicated by the