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Review

Advances in the discrete ordinates and finite volume methods for the solution of radiative heat transfer problems in participating media

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ABSTRACT

Many methods are available for the solution of radiative heat transfer problems in participating media. Among these, the discrete ordinates method (DOM) and the finite volume method (FVM) are among the most widely used ones. They provide a good compromise between accuracy and computational requirements, and they are relatively easy to integrate in CFD codes. This paper surveys recent advances on these numerical methods. Developments concerning the grid structure (e.g., new formulations for axisymmetrical geometries, body-fitted structured and unstructured meshes, embedded boundaries, multi-block grids, local grid refinement), the spatial discretization scheme, and the angular discretization scheme are described. Progress related to the solution accuracy, solution algorithm, alternative formulations, such as the modified DOM and FVM, even-parity formulation, discrete-ordinates interpolation method and method of lines, and parallelization strategies is addressed. The application to non-gray media, variable refractive index media, and transient problems is also reviewed.

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1. Introduction

Thermal radiation is an important heat transfer mode that is present in many problems of practical relevance, such as energy transfer in power plants, combustion chambers, high-temperature heat exchangers, rockets, fires, etc. Thermal radiation is often combined with conduction and/or convection, and other physical phenomena, such as turbulence and combustion may also be present. This implies that the equations governing all the relevant phenomena need to be solved simultaneously. This article, however, is only concerned with thermal radiation in participating media, which is governed by the radiative transfer equation (RTE).

The present work is concentrated on radiative heat transfer problems. We shall not address developments in the areas of atmospheric and solar radiation, or in other areas where the Boltzmann equation needs to be solved, e.g., neutron transport. Radiative transfer in porous media, plasmas and light propagation, with or without polarization, is also excluded from the present review. Similarly, applications to practical heat transfer problems, without new developments in the solution methods, and to coupled and inverse problems are also excluded from the present survey, except for exemplification purposes.

Many methods have been developed for the solution of radiative heat transfer problems in participating media. Among these, the discrete ordinates method (DOM) [1,2] and the finite volume method (FVM) [3,4] are among the most widely used ones. They provide relatively good accuracy for a wide range of problems, with moderate computational requirements, and are relatively easy to integrate in CFD codes. However, similarly to other methods for the solution of the RTE, that integration may lead to a significant increase of computational time, particularly for non-gray media, and to additional complexity when a finer grid is used for the fluid flow than for radiation calculations, e.g., to comply with the requirements of fine boundary layer resolution. The progress achieved in the DOM and FVM in the past few years is surveyed in the present article. Work previous to year 2000 is not addressed here, except when needed to complement the description of the most recent one.

The DOM and FVM are addressed together in the present paper, since they share many features, and the differences between them are small. The designation 'discrete ordinates' in the DOM strictly refers to the angular discretization procedure, in which the RTE is solved for a representative finite set of directions. A weight is assigned to every direction, such that the sum of the weights is equal to the area of the surface of a unit sphere, and integrals over a solid angle are evaluated using a quadrature method. In the DOM, the spatial discretization is usually carried out using the finite volume/finite difference method, but other options are possible. Methods that employ other spatial discretization procedures (e.g., finite element methods, spectral methods, meshless methods) while retaining discrete ordinates for angular discretization will not be addressed here. The designation 'finite volume' in the FVM implies that both the spatial and angular discretizations are performed using the finite volume discretization procedure. The radiation intensity over a solid angle is assumed to be constant, but its direction is allowed to vary. Hence, the DOM and the FVM differ on the angular discretization procedure, as described in Section 2. Only a brief description is presented here. The reader is referred to references [1–4] or text books [5,6] for further details, or to the references cited below for specific developments.

It is probably fair to say that advances in the DOM and FVM reported in the past decade or so have been more significant than for other methods. This is a consequence of the popularity of these methods, as mentioned above. Many of these advances have been aimed at the mitigation of the drawbacks of the methods, namely, by extending the application to more complex grid structures, proposing new spatial discretization schemes for the reduction of false scattering, or other angular discretization methods for the reduction of ray effects. Other developments are concerned with the solution algorithm, improvement of the accuracy, alternative formulations, parallel implementation, application to non-gray or variable refractive index media, and extension to transient problems. These advances are surveyed in the remainder of this paper.

2. Discretization procedure

A brief overview of the discretization of the RTE using the DOM and FVM is presented below. Although transient