Synopsis

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Combined Radiation, Conduction and/or Convection Heat Transfer in Participating Media

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Thermal radiation is one of the fundamental modes of heat transfer. It plays an important role in the design of high temperature engineering systems. The analysis and design of combustion chambers, porous burners and porous volumetric solar receivers, among many others, are some of the important application areas where consideration of thermal radiation is important.

Radiative heat transfer in a participating medium is a volumetric phenomenon. It is characterized by absorption, emission and scattering. The radiative transfer equation and the divergence of radiative heat flux are the two equations governing the radiative heat transfer in a participating medium. In a control volume, conservations of radiative energy in a given direction and over all directions are given by the radiative transfer equation and the divergence of radiative heat flux, respectively.

The equations governing the radiative heat transfer in a participating medium are integro-differential in nature and their solutions are difficult. The difficulty increases further if the thermophysical and the optical properties vary inside the medium and they are functions of temperature. Owing to the complexities in the solution, thermal radiation problems are solved using the approximate methods. In the literature more than 12 approximate methods exist, each of them having some advantages and disadvantages. All practical problems are solved using either of the methods.

The numerous advantages of the porous medium combustion over the free flame combustion have necessitated the need to perfect the design of appliances based on the porous medium combustion. The heat transfer analysis of the porous medium combustion is complex. It involves consideration of radiation along with conduction and convection. Among the three modes of heat transfer, radiation is the most difficult part to analyze. The detailed treatment of the porous medium combustion is laborious and time consuming. Among the three modes, the treatment of radiation is computationally the most expensive.

In the present work, with the final objective of doing the heat transfer analysis of the porous medium combustion, eight combined radiation, conduction and/or convection mode problems with varying degrees of complexities were considered. Radiative components in these problems were taken care of either by the collapsed dimension method (CDM) or the discrete transfer method (DTM). Further, these problems were chosen with an intention to extend the range of applications of the two methods. Finite difference based solvers were used to solve the energy equations.

The thesis is organized in 11 chapters. In the Introduction chapter, the need for analyzing heat transfer problems involving thermal radiation is justified and important works in this area are reviewed. In the second chapter, a general methodology is presented for the solution of any heat transfer problem involving thermal radiation. In such problems, how the radiative information required for the energy equation is computed using the CDM and the DTM is explained in some detail. Chapters 3 - 10 deal with eight different combined mode problems. Conclusions and recommendations are incorporated in Chapter 11. Problems considered in Chapters 3-10 are briefly described below.

The problem considered in Chapter 3 analyses the steady state conduction and radiation heat transfer in a planar absorbing, emitting and scattering medium. The boundaries of the medium are gray. One of the boundaries is maintained at a constant flux while the temperature of the other boundary is prescribed. The selection of this problem was intended to test the application of the CDM to problems with known flux at one of the boundaries.

Porous medium combustion involves consideration of heat generation inside the medium. In Chapter 4, the analysis was carried out for the transient conduction and radiation heat transfer with heat generation in a planar absorbing, emitting and scattering medium. The boundaries of the medium were at the prescribed temperatures. This problem was also intended to test the applicability of the CDM to this type of problem.

In the porous medium, depending on the shape and the size of the voids, different scattering theories have been proposed. Researchers have been using either Kamiuto's correlated scattering theory or Kaviany's scaling factor. However, no study had been reported to compare the results of the two theories. The problem considered in Chapter 5 deals with the analysis of transient conduction and radiation heat transfer in a planar porous medium and compares the results of the two scattering theories. The effects of variable porosity as well as constant porosity are also studied. The DTM was used to find the radiative information.

In flow through a porous medium with relatively high porosity and permeability, the boundary and the inertia effects are important and the fully developed velocity field is not uniform. This non-uniform velocity field affects heat transfer to or from the porous medium. With radiation, this situation had not been analyzed so far. Therefore, Chapter 6 deals with the effects of radiation along with conduction and convection in porous channel bounded by isothermal parallel plates in which the boundary and the inertia effects are important. The analysis was carried out for a wide range of the porous medium shape parameter (which is a function of the porosity and the permeability) including the two limits of the Poiseuille flow and the slug flow. The problem was solved by considering both solid and the fluid phases as a single continuum. The radiative information was found using the DTM.

In heat transfer problems involving radiation, there are sharp temperature gradients in the medium. Because of a large temperature variations in the medium, thermal conductivity of the medium does not remain constant. In such problems, the assumption of constant thermal conductivity is not appropriate. Chapter 7, therefore, deals with the effects of the temperature dependent thermal conductivity on transient conduction and radiation heat transfer in a planar absorbing, emitting and scattering medium.

In 1-D planar medium problems, computational time is not a major concern. However, in 2-D conjugate mode problems, calculation of radiative information is expensive. To extend the application of the CDM to 2-D conjugate mode problems, and also to find which of the two methods is computationally efficient, three benchmark problems were considered in Chapter 8. The performances of the two methods were analyzed over the different ranges of the radiative parameters. The CDM was found to be computationally efficient and thus a preferred method for 2-D problems.

In Chapter 9, effects of the variable thermal conductivity were analyzed for combined conduction and radiation heat transfer in a 2-D rectangular enclosure. The CDM was used for the calculation of radiative information.

Chapter 10 deals with the heat transfer analysis of 2-D rectangular porous burners. The gas and the solid phase were considered in non-local thermal equilibrium, and separate energy equations were used for the two phases. The solid phase was assumed to be participating, while the gas was assumed to be transparent to radiation. Radiative part of the energy equation was solved using the CDM. Effects of various parameters such as the aspect ratio, the extinction coefficient, the scattering albedo, the boundary emissivity and interface heat transfer coupling were studied on the performance of the burner. These parameters were found to have significant bearings on the temperature and heat flux distributions.

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