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A Monte Carlo simulation of radiative heat through fibrous media: Effects of boundary conditions and microstructural parameters

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ABSTRACT

This work reports on a Monte Carlo Ray Tracing (MCRT) simulation technique devised to study steady-state radiative heat transfer in fibrous insulation materials. The media consist of specular opaque fibers having unimodal/bimodal fiber diameter distributions. The simulations are conducted in 2-D ordered geometries, and the role of lateral symmetric or periodic boundary conditions are discussed in detail. Our results indicate that with the symmetric or periodic boundary condition, view factor $F_{i,i}$ should be excluded from the calculations leading to temperature prediction. This is especially important when the media are made of fibers arranged in ordered configurations. In agreement with our previous 3-D MCRT simulations, the 2-D MCRT simulations presented here reveal that heat flux through a fibrous medium decreases by increasing packing fraction of the fibers, when fiber diameter is kept constant. Moreover, increasing fibers' absorptivity was found to decrease the radiation transmittance through the media. In this work, we have also studied radiative heat transfer through bimodal fibrous media, and concluded that increasing fibers' dissimilarity increases energy transmittance through the media, if porosity and number of fibers are kept constant. It was also found that temperature of the fibers is almost independent of the media's porosity or diameter ratios.

1. Introduction

Fiber-based materials represent the single largest mediator of heat insulation in residential and industrial applications. Application of fibrous media extends from ordinary building insulations to the expensive high-temperature insulation materials deployed in the aerospace industry, such as Alumina fibers used in reusable launch vehicles for reentry flights [1–4].

At high temperatures, heat transfer through fibrous media occurs mostly via radiation. Traditional studies of radiative heat transfer in fibrous materials are based on developing lumped "radiation thermal conductivity" formulations, which strongly depend on certain empirical values that have to be obtained for each medium [5–10]. In such studies, thermal conductivity is calculated as a ratio of the measured heat flux to the temperature difference across the thickness of a medium. Although effective for comparing the performance of existing insulation materials, such lumped model approaches cannot be used for design and development of new materials.

Considering the media to be made of discrete arrays of packed particles, some studies have utilized Monte Carlo Ray Tracing (MCRT) techniques to simulate radiative heat transfer through granular porous beds [11–15]. The general approach in the MCRT method is to emit a large number of energy bundles from randomly selected locations on a given surface element and then to trace their progress through a series of reflections until they are finally absorbed on a surface element. There are also a few studies in which similar numerical techniques have been used to study radiation in fibrous insulation materials [16–19]. This includes our previous work, in which MCRT technique was used to simulate the flow of radiative heat through virtual 3-D geometries resembling the microstructure of a disordered fibrous medium [19]. In MCRT, energy bundles are emitted from the surface of a heat source (or the fibers), and their trajectories are tracked through the simulation domain. In this method, radiation rays interact directly with the fibers that lie in their paths. Parameters needed for MCRT include the basic microstructural parameters of the media such as fiber diameter, fiber optical properties, and material porosity and thickness. MCRT can therefore be used in developing fundamental relationships between a material's thermal performance and its microstructural building blocks.

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