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Modeling the role of microstructural parameters in radiative heat transfer through disordered fibrous media

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A B S T R A C T

Understanding the influence of microstructural parameters on the rate of heat transfer through a disordered fibrous medium is important for the design and development of heat insulation materials. In this work, by generating virtual 3-D geometries that resemble the internal microstructure of fibrous insulation materials, we simulated the influence of diameter, orientation, and emissivity of the fibers, as well as the media's porosity and thickness on the radiative heat transmittance. Our simulations are based on a Monte Carlo ray tracing algorithm that we have developed for studying radiative heat flow in 3-D disordered media. The media were assumed to be made up of cylindrical opaque fibers with specular surface. The advantage of our modeling approach is that it does not require any empirical input values, and can directly be used to isolate and study the role of individual microstructural parameters of the media. The major limitation of the model is that it is accurate as long as the fibers can be considered large relative to the wavelength of the incoming rays. Our results indicate that heat flux through a fibrous medium decreases by increasing the packing fraction of the fibers when the thickness and fiber diameter are kept constant. Increasing the fibers' absorptivity (or emissivity) was observed to decrease the radiation transmittance through the media. Our simulations also revealed that for constant porosity and thickness, the heat flux transmitted across the medium can be reduced by using finer fibers. The steady state temperature profiles across the thicknesses of media with different properties were obtained and found to be independent of the fibers' emissivity.

1. Introduction

Fibrous materials are distinguished by their light weight, conformability, high porosity, and high specific surface area (available surface area per unit volume). Such materials are used in a variety of applications including, but not limited to, filtration, drug delivery, protective clothing, acoustics, fluid absorption, and fuel cells. Fibrous materials are also widely used in heat insulation with applications in homes and industrial buildings. Expensive high-temperature insulation fibrous materials are also deployed in reusable launch vehicles for reentry flights [1–3].

Even though heat transfer through a fibrous medium is via both conduction (through the fibers and entrapped gas) and radiation, the contribution of heat conduction can be neglected in comparison to that of radiation in applications involving high-temperatures. Traditional studies of radiative heat transfer in fibrous materials have been based on developing "radiation thermal conductivity" values, which were often obtained via empirical methods or rigorous theories requiring input values that are often not readily available [4–8]. Radiation thermal conductivity is often calculated as the ratio of the measured heat flux to the temperature difference across the thickness of a medium. Such lumped model radiation thermal conductivity data are then used to develop mathematical functions with empirical/semi-empirical coefficients to predict the performance of fibrous materials used as radiative heat transfer insulation media. Although effective for comparing the performance of existing insulation materials, such lumped models are not always suitable for designing new materials. This is because with the lumped models, one cannot easily isolate the contributions of individual microstructural parameters (e.g., fiber diameter or orientation) to optimize/improve the design.

Treating a granular porous medium as discrete arrays of randomly packed particles, some studies have been conducted in the past to simulate radiative heat transfer using Monte Carlo ray tracing techniques [9–11]. There are also very few studies available in which similar numerical techniques have been used to study radiation in fibrous insulation materials [12–14], none of which were dedicated to studying the effects of different microstructural parameters on performance.

In the Monte Carlo ray tracing (MCRT) method, random rays are emitted from the surface of a heat source, and their trajectories are

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