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Analytical Monte Carlo Ray Tracing simulation of radiative heat transfer through bimodal fibrous insulations with translucent fibers

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ABSTRACT

In this study, a Monte Carlo Ray Tracing (MCRT) simulation technique is developed to study steady-state radiative heat transfer through fibrous insulation materials. The simulations are conducted in 3-D disordered virtual fibrous media with unimodal and/or bimodal fiber diameter distributions consisting of fibers whose surfaces are specularly reflective, and are translucent to Infrared (IR) radiation. Scattering within the realm of geometric optics is incorporated into our MCRT simulations using Snell's Law for ray refraction. Fibers' optical properties are obtained from Fresnel's law and Beer's law based on the refractive index of the material. Two different treatments of "high" and "low" conductivities are considered for the fibers and their effects are discussed. Our results indicate that heat flux through a fibrous medium with translucent fibers decreases with increasing packing fraction of the fibers. It was observed that IR transmittance through the media increases with increasing through-plane orientation of the fibers, but is independent of their in-plane orientations. It was also found that fiber orientation has generally a negligible effect on the temperature profile across the media's thickness. However, for the case of high-conductivity fibers, increasing fibers' through-plane orientation tends to flatten the temperature profile. The results obtained from simulating bimodal fibrous structures indicate that increasing the fiber-diameter dissimilarity, or the mass fraction of the coarse fibers, slightly increases the radiation transmittance through the media, and accordingly reduces the temperature gradient across the thickness. Our simulation results are compared with those from the two-flux model and good agreement is observed.

1. Introduction

Fibrous materials, thanks to their light weight and conformability, are widely used for heat insulation in residential and industrial applications. The large surface area of the fibers provides enough friction to suppress the convection, leaving radiation and conduction to be the only modes of heat transfer in fibrous insulation materials. Contribution of the latter modes of heat transfer, of course, depends on the temperatures imposed on the material—conduction becomes almost negligible when working with high temperatures [1–3]. In the current work, we limit our study to radiative heat transfer to better isolate the effects of each microstructural parameter of a fibrous material (e.g., fiber diameter or fiber orientation) on its performance as an insulation material.

Radiative heat transfer through fibrous insulation materials is often estimated using the Radiative transfer equation (RTE), in which the medium is assumed to be a pseudo-continuum [4]. The RTE is a highly involved integro-differential equation that can only be solved numerically. The solution procedure for this equation may need Monte Carlo Ray Tracing (MCRT), experimental, and/or analytical calculations to obtain the radiative characteristics (e.g., scattering phase function) of the media under consideration. Two major approaches have often been considered for determining radiative properties of fibrous insulation media. The first approach is to analytically determine the radiative properties of each individual fiber (or particle) using, for instance, the Electromagnetic wave theory (e.g., Mie theory), and then generalize the properties for the whole medium accounting for its morphology [5–14]. The second approach is to experimentally obtain transmittance and reflectance values for the fibrous medium and extract its radiative properties via an inverse method for solving the RTE [15–19]. MCRT has also been used to estimate the radiative properties of fibrous insulation media or to directly calculate the temperature or heat flux in a system in the absence of a continuum phase (i.e., the air entrapped between the fibers) [20–34].

The general procedure in MCRT is to emit a large number of energy bundles from randomly selected locations and directions from a given surface, and then trace their propagation through the

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