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Dual-scale 3-D approach for modeling radiative heat transfer in fibrous insulations

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ABSTRACT

In this work, a dual-scale computationally-affordable 3-D method is developed to simulate the transfer of radiative heat through fibrous media comprised of fibers with different diameters and orientations. The simulations start by generating a virtual fibrous material with specified microstructural properties and then compute the radiative properties of each fiber (i.e., effective phase function, as well as scattering and absorption coefficients) in the structure using the Mie Scattering theory. Considering independent scattering formulations for our fibrous media (media with high porosities), the radiative properties of the insulation material are computed by summing up the radiative properties of each individual fiber, after transforming the phase function values from the fiber's local 3-D coordinates system to a fixed global coordinates system. The radiative properties of the media are then used in the Radiative Transfer Equation (RTE) equation, an integro-differential equation obtained for computing the attenuation and augmentation of an InfraRed ray's energy as it travels through a fibrous medium. Using the Discrete Ordinate Method (DOM), the RTE is then discretized into a system of twenty four coupled partial differential equations and solved numerically using the FlexPDE program to obtain the rate of heat transfer through the entire thickness of the media. Studying media with different microstructural properties, it was quantitatively shown that increasing solid volume fraction, thickness, or fibers' through-plane orientation increases the rate of heat transfer through insulation. With regard to the role of fiber diameter, it was found that there exists a fiber diameter for which radiation heat transfer through a fibrous media is minimal, ranging between 3 and 10 μm for glass fibers operating in a temperature range of about 340–750 K.

1. Introduction

Fibrous materials are the most common insulations currently on the market, thanks to their low production cost and minimal weight. Fibrous insulations can efficiently suppress the convective mode of heat transfer because of the significant friction the fibers cause against fluid motion, leaving radiation and conduction as the only modes of heat transfer (this can easily be shown by calculating the Rayleigh number as defined by Nield and Bejan [1] for heat transfer between two parallel horizontal plates filled with a porous medium). Fibrous insulations are often composed of glass fibers, polymeric fibers, or mineral wool. Depending on the application (i.e., temperature range and geometrical restrictions), different insulation materials, in terms of both the parent materials and the microstructural parameters (fiber diameter, porosity, fiber orientation...), are needed to efficiently block the transfer of heat. Designing efficient fibrous insulations for a given application requires quantitative knowledge of the role played by each of the above parameters in blocking the transfer of heat [2]. In most reported studies, on the other hand, an insulation material has been treated as a lumped system. The usual outcome of a lumped-model approach is an "effective thermal conductivity" which combines the contributions of each individual parameter in blocking conductive and radiative heat into a single value. Obviously, such an approach does not provide clear guidelines for improving the performance of a product as it does not isolate the source of a problem [3–5].

The complexity of studying heat transfer through a disordered fibrous media lies mostly with the radiation component. This is because porosity of insulation media is normally very high and therefore contribution of the solid phase (i.e., fibers) in heat conduction through the media is negligible compared to that of the interstitial fluid (normally air), unless the fibers are highly conductive (e.g., Aluminum or Steel fibers), which is not very common [2]. Therefore, one can estimate the rate of heat conduction through most insulation media using only the air conductivity and the material's thickness. The radiative component of heat however, varies very differently in insulation media with different fibrous

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