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A simple simulation method for designing fibrous insulation materials

R. Arambakam [a], H. Vahedi Tafreshi [a,*], B. Pourdeyhimi [b]

[a] Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University, Richmond, VA 23284-3015, United States
[b] Nonwovens Cooperative Research Center, The Nonwovens Institute, NC State University, Raleigh, North Carolina 27695-8301, United States

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ABSTRACT

Conductive heat in a fibrous material travels through both the air (interstitial fluid) and the fibers (solid phase). The numerical simulations reported in this paper are devised to study the effective thermal conductivity of fibrous media with different microstructural parameters. Simulations were conducted in 3-D fibrous geometries resembling the microstructure of a fibrous material. Assuming that the heat transfer through the interstitial fluid is independent of the geometrical parameters of the solid phase (for when the porosity is held constant), the energy equation was solved only for the solid structures, and the resulting values were used to predict the effective thermal conductivity of the whole media. This treatment allows us to drastically reduce the computational cost of such simulations. The results indicate that heat conduction through the solid fibrous structure increases by increasing the material's solid volume fraction, fiber diameter, and fibers' through-plane orientations. The in-plane orientation of the fibers, on the other hand, did not show any significant influence on the material's conductivity. It was also shown that the microstructural parameters of fibrous insulations have negligible influence on the material's performance if the conductivity of the solid phase is close to that of the interstitial fluid.

1. Introduction

Insulation materials are often composed of glass fibers, polymeric fibers, or mineral wools. However, in some applications involving high temperatures, steel fibers, alumina fibers, and/or other similar temperature-resistance materials have also been used for insulation [1,2]. Heat transfer in a fibrous insulation material occurs through conduction, convection, and radiation. The contribution of each of these modes of heat transfer varies depending on the application. Convection heat transfer can often be neglected since the friction between the fibers and the interstitial fluid may suppress convective motions inside the media. While radiative heat transfer is generally important in high-temperature applications (see [3,4] for instance), conductive heat transfer is often the mechanism by which heat transfers through fibrous materials in temperatures near or below room temperature [2].

Conductive heat transfer occurs through the fibers and the interstitial fluid. Therefore, an effective thermal conductivity, which includes the contributions of the solid and the interstitial fluid, is often defined and used in discussing the performance of an insulation material. The effective thermal conductivity of a fibrous material is greatly influenced by its microstructural parameters such as solid volume fraction (SVF), thermal conductivity of the solid fibers and the interstitial fluid, fiber diameter, and fiber orientation. Obviously, for media consisting of more than one type of fibers, i.e., composite insulation media, there are more parameters influencing the insulation performance [5].

Conductive heat transfer through fibrous insulation materials has been studied analytically, numerically, and experimentally. Analytical models have been developed and compared with experiment to predict thermal insulation properties in terms of SVF and thermal conductivity of solid and interstitial phases by [6,7] among others. There are also analytical studies dealing with the effects of fiber orientation and fiber length on thermal conductivity (see for instance [8,9]). There are also numerous predominantly experimental studies reporting on the thermal insulation properties of different fibrous materials obtained, for instance, by a guarded hot plate apparatus [10,11]. In such studies, performance of the material in blocking conductive and radiative heat transfer is often lumped together in the form of an effective conduction–radiation thermal conductivity [10,11]. Improved testing procedures and more advanced macroscale numerical simulations have also been developed for studying the combined conduction–radiation heat transfer through fibrous media with a specific attention to the effects of operating temperature and pressure on the performance of high-temperature insulations by [12,13].

To better investigate the effects of microstructural parameters on the performance of fibrous insulation materials exposed to conductive heat flow, microscale 3-D simulations are developed and reported in the current paper. The study presented here completes

* Corresponding author. Tel.: +1 804 828 9936; fax: +1 804 827 7030.
E-mail address: htafreshi@vcu.edu (H. Vahedi Tafreshi).
URL: http://www.people.vcu.edu/~htafreshi/ (H. Vahedi Tafreshi).

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