Materials and Design 44 (2013) 99–106

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

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

ARTICLE INFO

Article history:
Received 30 June 2012
Accepted 26 July 2012
Available online 3 August 2012

Keywords:
Conductive heat transfer
Fibrous materials
Insulation materials
Numerical simulation

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).

0261-3069/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2012.07.058

Nomenclature

α	solid volume fraction
k_g	conductivity of the interstitial fluid
k_f	fiber conductivity
k_s	conductivity of solid fibrous structure
k_{eff}	effective thermal conductivity of fibrous materials
T	temperature
ΔT	temperature difference
q	heat flux
L	thickness of the material
A	area of the hot or cold plates
d_f	fiber diameter
d^*	non-dimensionalized allowable distance between two fibers at their crossover point

the previous studies by the authors, in which an inexpensive Monte Carlo Ray Tracing (MCRT) algorithm for simulating radiative heat transfer through fibrous media have been developed [14,15]. Such a simulation methodology is valuable as it allows one to isolate the effect of each individual parameter and study its influence on the performance of the whole media (i.e., the fibrous structure and the interstitial fluid). Since heat transfer through the interstitial fluid takes place independently from the geometrical parameters of the solid phase (for a given porosity), the energy equation was solved for the solid phase (fibrous structure) only. The conductivity values obtained for the solid structure can then be easily combined with the conductivity of the interstitial fluid to predict the effective thermal conductivity of the whole media if needed. This treatment allows us to significantly reduce the computational cost of such simulations, and thereby to make a comprehensive parameter study feasible. In particular, with this treatment, one can consider much larger (and so more realistic) Representative Elemental Volumes (REVs) for simulation to reduce the statistical errors associated with each simulation, and consequently produce a large simulation dataset with less computational time.

The remainder of this paper is organized as follows. Complete descriptions of the structure generation, structure characterization and the heat transfer simulation setup are given in Section 2. The results and discussions are given in Section 3 followed by conclusions in Section 4.

2. Steady state conduction in fibrous media

Conductive heat travels through both the fibers and the interstitial fluid (often air). Conductive heat transfer formulations for porous media are often developed considering heat flowing in parallel or series paths. When heat flow is assumed to occur in a series mode, then flow of thermal energy is assumed to occur in sequence through a series of layers. Conductive heat transfer is said to occur in parallel mode if the flow of heat is described through simultaneous parallel paths through the medium. In calculations the thermal conductance of each path is added to derive a total rate of heat flow through the entire medium [6,7]. The most basic expression (Eq. (1)) for defining an effective thermal conductivity in porous media is developed based on a weighted average of the thermal conductivity values of the fibers and interstitial fluid [6,7], and heat transfer is assumed to occur in a parallel mode through solid and the interstitial fluid.

$$k_{eff} = \alpha k_f + (1 - \alpha) k_g \tag{1}$$

The major problem with this equation is that it assumes the solid phase to act like a solid block connecting the heat source to the heat sink, neglecting the fact that heat has to flow through a number of small fiber-to-fiber contact areas before it can reach the sink. Therefore, one can expect that the term αk_f in the above equation significantly over-predicts the conductivity of the solid phase. The second term in the right-hand side of Eq. (1), on the other hand, is expected to be quite accurate in predicting the conductivity of the fluid phase. This is because the interstitial fluid does connect the source and sink plates with no considerable bottle-necks in the heat flow path, at least for most practical fibrous structures (i.e., porous media with very low solid volume fractions).

2.1. Modeling conductive heat transfer in fibrous media

The internal structure of most fibrous materials fall into one of three main categories: unidirectional structures, where axes of all cylindrical fibers are parallel with one another, layered structures, where axes of cylindrical fibers lie randomly in parallel planes often perpendicular to the heat flow direction, and three-dimensionally isotropic structures, where fibers' axes can be randomly oriented in any direction (see Fig. 1) [16].

An in-house MATLAB code was developed to generate fibrous structures with different structural parameters—virtual fibrous media with controlled porosity, thickness, and fiber diameter, as well as fibers in-plane and though-plane orientations. The media generation process is based on the so called μ-randomness algorithm and is fully described in previous publications [16,17]. Due to the randomness of the generation process, each simulation is repeated at least three times to reduce the statistical uncertainty of the results presented. After each fibrous structure is produced, a script file is produced for the GAMBIT software in which the actual SVF of the structure is measured and also is meshed using tetrahedral elements and exported to the Ansys Fluent code for heat transfer calculations.

The fibrous structures were considered to be sandwiched between a hot and cold plate as shown in Fig. 2. A temperature gradient is imposed across the thickness of the media by assigning different temperatures to the hot and cold plates. The steady-state heat equation is solved for the flow of conductive heat through the fibers using the Ansys Fluent CFD code.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \tag{2}$$

Symmetry boundary condition has been considered for all lateral boundaries of the simulation domain. Although no plane of symmetry can actually exist in a disordered fibrous structure, the error associated with such a boundary condition is negligibly small when a large REV is considered for the simulations as the heat flow is mainly in the direction of the macroscopic temperature gradient (i.e., through-plane direction) [18]. The boundary conditions considered in the current simulations are shown in Fig. 2. An arbitrary fiber thermal conductivity of 0.2 W/m K (polypropylene) and a fiber diameter of 8 μm were considered unless otherwise specified. The temperatures of the hot and cold plates are also arbitrarily chosen to be 330 K and 300 K, respectively. Since no air is considered in the calculations, heat transfer between the hot and cold plates is due only to conduction in the solid phase.

$$k_s = \frac{qL}{A\Delta T} \tag{3}$$