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Predictions of effective thermal conductivities for three-dimensional four-directional braided composites using the lattice Boltzmann method

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ABSTRACT

A multiple-relaxation-time lattice Boltzmann model with an off-diagonal collision matrix is adopted to predict the effective thermal conductivities of anisotropic heterogeneous materials with anisotropic components. The half lattice division scheme is used to handle the internal boundaries to guarantee the heat flux continuity at the component interfaces. Accuracy of the model is confirmed by comparing with benchmark results and existing simulation data. The present method is then employed to predict the transverse and longitudinal effective thermal conductivities of three-dimensional four-directional (3D4D) braided composites. Experiments based on the Hot Disk method are also conducted to obtain the transverse and longitudinal effective thermal conductivities of the materials. The numerically predicted results fit the experiment data well. Then, influences of fiber volume fractions, interior braiding angles and interface thermal contact resistance on the effective thermal conductivities of 3D4D braided composites are studied. The results show that the effective thermal conductivity along the transverse direction increases with the fiber volume fraction and interior braiding angle; while the longitudinal one increases with the fiber volume fraction but decreases with the increasing interior braiding angle. A larger interface thermal contact resistance leads to a smaller effective thermal conductivity. Besides, for anisotropic materials, the effective thermal conductivity obtained by the periodic boundary condition is different from that obtained by the adiabatic boundary condition.

1. Introduction

The three-dimensional four-directional (3D4D) braided composites are anisotropic heterogeneous materials composed of the matrix and braiding yarns. They have been widely applied in aeronautics and astronautics due to their high strength and low density [1]. The braiding yarns, one of the components in 3D4D braided composites, are anisotropic with different thermal conductivities along the transverse and longitudinal directions [2,3]. Heat transfer in each anisotropic component has preferable directions, and it needs a thermal conductivity matrix to fully describe the local property of components. Besides, the continuity of the normal heat flux and temperature should be ensured at the component interfaces. The thermal properties of the 3D4D braided composites are anisotropic along the transverse and longitudinal directions. For such anisotropic heterogeneous materials with anisotropic components, the effective thermal conductivity along the specified direction is an important parameter that can quantitatively evaluate the heat transfer capacity of composites. Here, several concepts are emphasized to avoid confusion. The heterogeneous material refers to a composite material with different components, and the homogenous material refers to the material with only one component. Anisotropic heterogeneous materials with anisotropic components refer to the composite materials of which the overall thermal properties are anisotropic and their components are also anisotropic. Anisotropic heterogeneous materials with isotropic components refer to the composite materials of which the overall thermal properties are anisotropic but their components are isotropic.

The lattice Boltzmann method (LBM) is an effective approach to solve the Navier–Stokes equations. It has been widely used to solve the conventional fluid flows [4,5], fluid flows in porous mediums [6,7], multiphase flows [8–10], and recently has been applied to investigate the effect of magnetic field on the behavior of the nanofluid [11,12]. Moreover, the LBM has also been used successfully in solving energy transport or mass diffusion problems. Xuan et al. [13] investigated the mass transfer process of volatile organic compounds in porous media based on the LBM. Chen et al. [14] adopted the LBM to predict the effective diffusivity of the porous gas

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Nomenclature

a, b, m, h	characteristic length of the unit cell, mm
c	pseudo sound speed, m/s
c_p, ρc_p	heat capacity J/(kg·K), volumetric heat capacity, J/(m^3·K)
D, d	thermal diffusivity, m^2/s, diameter of fiber, mm
$\boldsymbol{e}$	discrete velocity
f, f^{eq}	temperature distribution function, equilibrium distribution function
L	thicknesses of materials, m
$\boldsymbol{m}$	moment vector
$\mathbf{M}$	transformation matrix
q	heat flux, W/m^2
$\mathbf{S}$	relaxation time matrix
t, δt, δx	time, time step, space step
T	temperature, K
Ω	collision matrix
β, γ	oblique angle, interior braiding angle, °
ε, κ	constants, $\varepsilon = 2\ \kappa$, and $\kappa = 1/8$
ϕ	volume fraction
λ	thermal conductivity, W/(m·K)
τ	relaxation time coefficient

Subscript

α	direction of the temperature distribution function
m	matrix
f	fiber
i, j	number index
x, y, z	direction index
$\bar{\alpha}$	directions opposite to α
η, ζ	principle axis of heat conduction
e	effective
T	transverse
L	longitudinal
fy	fiber volume fraction of braiding yarn
ya	yarn volume fraction of the unit cell

diffusion layer in fuel cell. Wang et al. [15] proposed a LB algorithm to deal with the fluid–solid conjugate heat transfer problem, which can ensure the heat flux and temperature continuity at the interfaces. As for the heterogeneous materials with isotropic components, many studies have been conducted to predict their effective transport property. In particular, Wang et al. [16] proposed a LB model to predict the effective thermal conductivity for granular structures, netlike structures and fibrous structure composite materials. In the model of Wang et al. [16], the original LB Bhatnagar–Gross–Krook model was adopted, which only has a single-relaxation-time coefficient without sufficient parameters to fully describe the anisotropic heat transfer in anisotropic materials. Several studies have been conducted on the solution of anisotropic heat transfer equation using the LBM. Zhang et al. [17,18] proposed a LB model in which the relaxation time coefficients are assumed to be directionally dependent and this model ensured that the collision is mass-invariant. Ginzburg et al. [19] presented two LB models, the equilibrium-type and the link-type models, to solve the anisotropic heat transfer problems. But these models all suffer the instability and poor application flexibility [20]. Recently, the multiple-relaxation-time (MRT) LB model has been adopted for heat transfer due to its higher stability and accuracy than the single-relaxation-time model [21,22]. Yoshida and Nagaoka [20] developed a MRT LB scheme using a collision operator with off-diagonal components, making it possible to solve the anisotropic heat transfer problems, but it is only suitable for the homogeneous materials. As for the heterogeneous materials with anisotropic components, it will lead to heat flux discontinuity at the interfaces if the heat transfer at the interface is not properly treated [23].

There have been some studies using finite element methods to predict effective thermal conductivity of 3D4D braided composites [3,24,25]. However, it is quite difficult for the finite element method to consider the thermal contact resistance at the internal interface and to predict the effective thermal conductivity of heterogeneous materials with randomly distributed anisotropic components, such as needled C/SiC composites [26]. The LBM is particularly suitable for the heat and mass transfer in complex materials and has the ability to deal with the thermal contact resistance at the internal interface, and thus the present study focuses on developing a LB model for 3D4D braided composites with anisotropic components. The developed LB model can be also adopted to predict the effective thermal conductivity of the needled C/SiC composites. Besides, the previous numerical results based on the finite element method were not compared with the corresponding experimental data, and in the present study, such comparisons are also conducted.

The MRT model developed by Yoshida and Nagaoka [20] and the treatment for the internal interfaces should be combined to deal with such heterogeneous materials with anisotropic components. The single-relaxation-time LBM adopted by Wang et al. [15] is only suitable for the materials with isotropic components, and it has been used to predict the effective thermal conductivity of the isotropic heterogeneous materials with isotropic components [27] and the directional effective thermal conductivity of the anisotropic heterogeneous materials with isotropic components [28].

In the present paper, a multiple-relaxation-time LB model combined with the 'half lattice division scheme' treatment for internal interfaces is adopted to predict the effective thermal conductivity of the anisotropic heterogeneous materials with anisotropic components. The 'half lattice division scheme' first proposed by Wang et al. [15] is to handle the internal interfaces between the isotropic components. In the present paper, it is extended to deal with the internal interfaces between the anisotropic components. With the 'half lattice division scheme' method, the temperature and heat flux can be directly obtained from the local temperature distribution functions without the calculations of the finite difference, which is important for the continuity of temperature and heat flux at the interfaces (will be discussed at Section 2.3). In addition, to verify the reasonability and accuracy of the present method, several benchmarks are simulated, and then experiments based on the Hot Disk method are conducted to measure the effective thermal conductivity of 3D4D braided composites (Section 4.3). The influences of the fiber volume fraction, interior braiding yarns and interface thermal contact resistance on the effective thermal conductivity are also examined in this study (Section 5).

2. Numerical method

2.1. Governing equation

The governing equations for anisotropic heat conduction in multicomponent systems, e.g., the matrix and reinforced fibers, without any heat source can be expressed as

$$\frac{\partial T_m}{\partial t} = \frac{\partial}{\partial x_i}\left((D_{ij})_m \frac{\partial T_m}{\partial x_j}\right) \tag{1}$$