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Calculation of high-temperature insulation parameters and heat transfer behaviors of multilayer insulation by inverse problems method

Huang Can, Zhang Yue *

Key Laboratory of Aerospace Materials and Performance (Ministry of Education), School of Materials Science and Engineering, Beihang University, Beijing 100191, China

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Abstract In the present paper, a numerical model combining radiation and conduction for porous materials is developed based on the finite volume method. The model can be used to investigate high-temperature thermal insulations which are widely used in metallic thermal protection systems on reusable launch vehicles and high-temperature fuel cells. The effective thermal conductivities (ECTs) which are measured experimentally can hardly be used separately to analyze the heat transfer behaviors of conduction and radiation for high-temperature insulation. By fitting the effective thermal conductivities with experimental data, the equivalent radiation transmittance, absorptivity and reflectivity, as well as a linear function to describe the relationship between temperature and conductivity can be estimated by an inverse problems method. The deviation between the calculated and measured effective thermal conductivities is less than 4%. Using the material parameters so obtained for conduction and radiation, the heat transfer process in multilayer thermal insulation (MTI) is calculated and the deviation between the calculated and the measured transient temperatures at a certain depth in the multilayer thermal insulation is less than 6.5%.

1. Introduction

Thermal insulation is a subject of great interest to the new generation of reusable launch vehicles and thermal protection systems,[1] which can sustain severe heating during the process of aerodynamic reentry when the surface temperature is high. The heat transfer inside thermal insulators is composed of conduction, natural convection and radiation. Convection can be neglected[2,3] in porous media at high temperatures and

* Corresponding author. Tel.: +86 10 82339109.
E-mail addresses: canhuangcan@163.com (C. Huang), zhangy@buaa.edu.cn (Y. Zhang).

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atmospheric pressure. Previous studies show that radiation is the dominant mode of heat transfer when the temperature is higher than 573 K.[4] Heat transfer through fibrous media has displayed that radiation accounts for 40%–50% of the total heat transfer inside light-weight fibrous thermal insulations at moderate temperatures.[5] The complex coupling of conductivity, convection and radiation, especially the radiation, makes the analysis and the design of thermal insulations difficult.

Heat transfer through fibrous and multilayer insulations has been investigated by various researchers, both experimentally and analytically during the last 30 years. Two main problems exist in the characterization of the thermal insulations. As the effective thermal conductivity (ETC) measured by experimental apparatus cannot be directly used to analyze the thermal behavior of high-temperature insulation, parameters measured need to be separated into two parts: radiation and thermal conductivity parameters. And the low value of effective thermal conductivity makes it difficult to obtain thermal conductivity at a certain temperature. Lee and Cunnington[6] provided a comprehensive review of heat transfer in generally porous materials. Walter et al.[7] used the first-principle approach to analyze combined heat transfer in a highly porous silica insulation material called LI900. The two flux approximation was frequently used to describe the thermal behavior of fibrous insulation. Tong et al.[8,9] used the two flux model which assumed a linearized anisotropic scattering to model heat transfer inside fibrous thermal insulation and compared the calculated values with experimental data up to 450 K at 10^5 Pa. Zhao et al.[10–12] used the two flux model that assumed a modified factor of extinction and an equivalent albedo of scattering to model the heat transfer of fibrous insulation used in thermal protection. Daryabeigi[1,13] modeled heat transfer in alumina fibrous insulation to predict effective thermal conductivities at gas pressures 10^{-2} Pa and 10^{-5} Pa and at temperatures up to 1273 K. The model was based on a modified two flux approximation assuming anisotropic scattering and gray medium. The two flux approximation contained such parameters as the specific extinction coefficient, albedo of scattering, backscattering fraction, solid conduction exponent term, etc. Generally, these parameters were obtained by experimental and numerical methods. For multilayer thermal insulations (MTIs), Spinnler et al.[4,14] modeled heat transfer in multilayer thermal insulations using a radiation scaling method. The model was used to calculate the effective thermal conductivities at temperatures between 473 K and 1273 K and make optimization of multilayer thermal insulation. Li and Cheng[15] developed a model using an energy balance equation, which was concerned with radiation emissivity, perforation coefficient and neglected the radiation flux in spacer materials, for steady temperature calculation of the insulation layer in a multilayer perforated insulation material at 300 K and made optimum design of the multilayer perforated insulation material.

In this work, we established a model based on the finite volume method to investigate the thermal behaviors of both the fibrous insulation and multilayer thermal insulation, which contains the following thermal parameters: the effective conductivity of the solid and gas, equivalent radiation transmittance, absorptivity and reflectivity. These thermal parameters can be used to study the thermal behavior of high-temperature insulations, and to solve the difficulty of analyzing thermal behavior with effective thermal conductivity. The relationship between temperature and thermal conductivity of the solid and gas was also investigated to calculate the conductivity at a certain temperature. Experimental and numerical methods were combined to optimize the parameters of high-temperature insulation by an inverse problems method. Finally, the calculated results were compared with the measured data under different conditions.

2. Experimental apparatus

In this work, the effective thermal conductivity of thermal insulation was measured according to YB/T4130-2005 in Luoyang Institute of Refractories Research, China.[16] The effective thermal conductivity was measured under atmospheric pressure with the nominal hot temperatures set at 473 K, 573 K, 673 K, 773 K, 873 K, 973 K, 1073 K, 1173 K, 1273 K, 1373 K and 1473 K. The uncertainty of the measured effective thermal conductivity was approximately 8%.

In order to study the transient thermal behavior of multilayer thermal insulation, a graphite heater (20 WM electric arc wind tunnel) was used to provide a time-dependent surface temperature. The multilayer thermal insulation was composed of 5 mm calcium silicate and aluminum silicate fibers (CA) and 10 mm nanoporous silica fibers (NP2) with carbon screens per 2 mm. The multilayer thermal insulation was placed between a septum plate and a water-cooled plate. Thermocouples were used to measure the front and back surface transient temperatures as well as the internal temperature responses of multilayer thermal insulation at the depth of 5 mm as shown in Section 6.

3. Theoretical analysis

Heat transfer through high-temperature insulation is composed of conduction, natural convection and radiation. Stark and Fricke pointed out that natural convection heat transfer can be neglected[2] through porous media. Therefore, the governing conservation of the energy equation for one dimensional heat transfer inside thermal insulations which combines conduction and radiation can be described as[17,18]:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{\mathrm{c}} \frac{\partial T}{\partial x}\right) - \frac{\partial q_{\mathrm{r}}}{\partial x} \tag{1}$$

subject to the following initial and boundary conditions:

$$\begin{cases} T(x,0) = T_0(x) \\ T(0,t) = T_1(t) \\ T(L,t) = T_2(t) \end{cases} \tag{2}$$

where ρ is density; c is specific heat capacity; k_{c} is the effective conductivity of the solid and gas; q_r is the radiation heat flux;

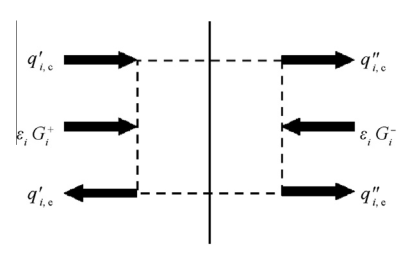

Fig. 1 Energy balance of layer *i*.