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Heat transfer through fibrous assemblies incorporating reflective interlayers

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ABSTRACT

Fibrous insulation has many applications including functional protective clothing, sleeping bags, buildings and construction, and aircrafts, particularly under extreme climatic conditions. It has been realized that reflective interlayers can be incorporated into the fibrous materials to block radiative heat transfer. However, since reflective interlayers generally have greater thermal conductivity than the bulk fibrous materials, the optimization of the construction of the fibrous insulation is important in maximizing the overall thermal insulation. In order to analyze this complex optimization problem, a two-flux radiative heat transfer model was built for the heat transfer through fibrous assemblies incorporating reflective interlayers. By using finite control volume method, the solution was obtained. After validation it was applied to predict the optimum constructional parameters of such an assembly for maximizing thermal insulation. It was found that (1) although extinction coefficient of Al-coated interlayer fibers decrease unidirectionally as the fiber diameter increases, the total heat flux first decreases and then increases with minimum heat flux at the fiber diameter of about 2 μm; Consequently, the thermal resistance reaches a maximum value when the fiber diameter *d* is about 2 μm; (2) the optimum construction is determined by the balance of the weakening of conductive thermal resistance and enhancement of the radiative thermal resistance as a result of incorporating thin reflective interlayers. For relatively thick reflective interlayer, the assembly with lower interlayer fiber volume fraction has a higher thermal resistance. On the other hand, for very thin reflective interlayers, relatively high fiber volume fraction is beneficial to the overall thermal insulation.

1. Introduction

Fibrous insulation is used in many applications, such as functional protective clothing, sleeping bags, buildings and construction, and aircrafts, particularly under extreme climatic conditions. Radiation plays a significant role in the heat transfer through fibrous materials [1]. It is well known that metalizing fibers can greatly improve the radiation blocking efficiency for its high reflection performance [2–4]. For thick thermal insulation materials, reflective interlayers can be incorporated to block radiative heat transfer [2,5]. Nevertheless, because reflective interlayers are generally more heat conductive than the bulk material, too many reflective interlayers may reduce the overall thermal insulation. In order to achieve the maximum thermal insulation of fibrous assembly incorporating reflective interlayers, the constructional parameters of the assembly (e.g. number of reflective interlayers, its thickness and fiber volume fraction) should be optimized.

For the theoretical analysis of the fibrous insulations, the two-flux radiative thermal model has been used in the past three decades by researchers, such as Farnworth [6], Daryabeigi [7], Spinnler et al. [8] and Bhattacharjee and Kothari [9]. Wu et al. [5] adopted Farnworth's two-flux model to solve the optimization problem for non-reflective interlayer structures by using a finite volume method. Their solution is not valid, however, for reflective materials, because the scattering effect of radiation by fibers was not taken into account. However, up to now, the study on fibrous assembly incorporating reflective interlayers by using this method towards numerical solution has not been reported yet.

Therefore, this paper developed a two-flux model to analyze the radiative heat transfer through fibrous assembly incorporating reflective interlayers. By computing the thermal resistances of the fibrous assemblies with different constructional parameters, the optimal design of such an assembly is derived and analyzed.

2. Mechanisms and mathematical formulation

The type of fibrous assembly incorporating reflective interlayers is illustrated in Fig. 1. The primary material is evenly separated by

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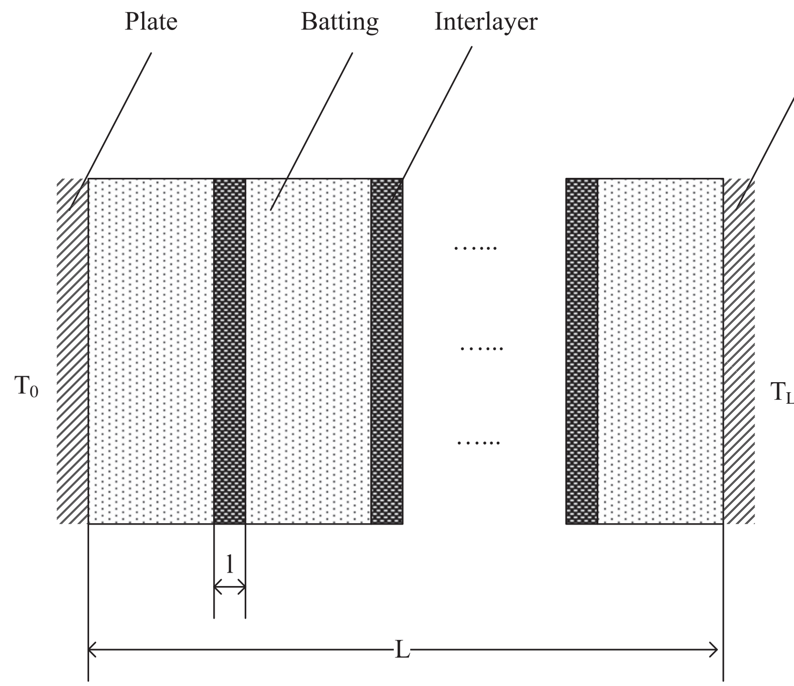

Fig. 1. Fibrous assembly incorporating reflective interlayers.

thin reflective interlayers, the whole system being sandwiched between two plates at temperatures T_0 and T_L, respectively.

2.1. Heat transfer equations

In this paper, only conductive and radiative heat transfers are considered since convective heat transfer in porous fibrous materials is negligible in many applications. The thermal conductivity of the porous material (k) can be taken as a combination of that of air (k_a) and fibers (k_f), viz:

$$k = (1 - f)k_a + fk_f \tag{1}$$

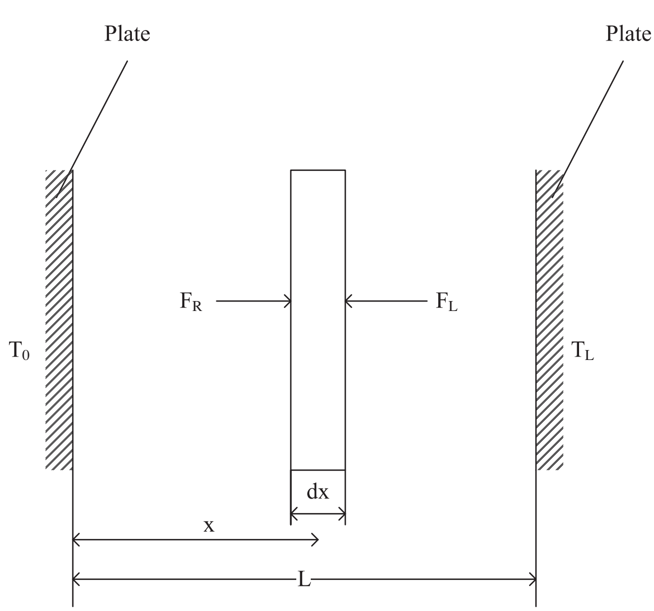

Fig. 2. Radiative heat transfer through the multilayer fibrous assembly.

where, f is fiber volume fraction.

Consider a fibrous assembly consisting of multiple layers of fibrous materials having varying properties as shown in Fig. 2. For a small element with thickness d_x in a particular layer, a two-flux radiative heat transfer model approach can be applied.

Let F_R represent the radiative heat flux from the left to the right, and F_L the radiative heat flux towards the left. After F_R has traveled from the left to the right of the element, it is enhanced by the emission and internal scattering from this element to the right, while being attenuated by the absorption and scattering by this element to this incident heat flux.

Because of the spectral dependency of the radiative properties, the rigorous equation determining F_R in the form of monochromatic radiation is as follows [1]:

$$\frac{dF_{R,\lambda}}{dx} = 2\sigma_{a,\lambda}e_{b,\lambda} + 2\sigma_{s,\lambda}b_\lambda F_{L,\lambda} - 2\sigma_{a,\lambda}F_{R,\lambda} - 2\sigma_{s,\lambda}b_\lambda F_{R,\lambda} \tag{2}$$

where $\sigma_{a,\lambda}$ and $\sigma_{s,\lambda}$ are the volumetric spectral absorption and scattering coefficients, respectively, averaged over all incident radiation, b_λ is the fraction of radiation scattered backwards, $e_{b,\lambda}$ is the spectral blackbody emissive power and λ denotes wavelength dependence.

In the equation, the first item on the right side represents the radiation emission by the small element; the second item is the energy gain by back scattering of $F_{L,\lambda}$; the third one is the loss by absorption and the final is the loss by the back scattering of $F_{R,\lambda}$. It is obviously more rigorous than radiative conductivity model and Farnworth' model [6] for the reason that radiative conductivity model is only valid for optically thick medium, and Farnworth's model neglected the scattering effect of the fibers, only considered the absorption effect in terms of absorption constant for the attenuations.

In the same way, for F_L:

$$-\frac{dF_{L,\lambda}}{dx} = 2\sigma_{a,\lambda}e_{b,\lambda} + 2\sigma_{s,\lambda}b_\lambda F_{R,\lambda} - 2\sigma_{a,\lambda}F_{L,\lambda} - 2\sigma_{s,\lambda}b_\lambda F_{L,\lambda} \tag{3}$$

By integration over the wavelengths, it follows that: