HEAT TRANSFER ANALYSIS OF INSULATION MATERIALS WITH FLEXIBLE MULTILAYERS

by

Jin-Jing CHEN[a,b*], Zheng GUO[a,b], and Wei-Dong YU[c]

[a] College of Textiles, Zhongyuan University of Technology, Zhengzhou, China
[b] Henan Key Laboratory of Functional Textiles Material, Zhengzhou, China
[c] College of Textiles, Donghua University, Shanghai, China

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A new flexible multilayer thermal insulation material is presented for applications at harsh environment as high as 433 K or as low as 123 K. A heat transfer model is established and solved to study heat transfer through the material, including radiation, solid heat transfer and gas heat transfer. Comparison between the experimental results and the theoretical prediction shows that the model is feasible to be applied in engineering. The temperature distribution of samples with 10, 15, 20, 25, 30 layers, respectively, the radiation, solid and gas heat transfer of a sample with 10 layers are analyzed at harsh conditions (123 K and 433 K) and the normal condition as well. The theoretical thermal analysis provides an active instruction to an optimal design of such protective materials.

Key words: *flexible, multilayer insulation material, heat transfer, high-low temperature*

Introduction

Protection of human has been caught much attention in protective material research, and flexible protective material is a key factor for normal moving in special occasions to explore the world and the universe. Most of the flexible protective materials consider the very requirement of these special applications. Such materials should be light to reduce the burden, flexible to reduce the barriers and energy consumption, protective to all kinds of hot, light and radiation. It also requires to protect force, organisms or harmful gas, liquid, and solid infringement. Overall, temperature protection including cold and hot environment is the most basic content in protection of human isolation.

The flexible material has soft, light and good insulation performance, and it is sufficient to form the thermal protection materials separately [1]. Therefore, the most thing people want to attain and study constantly is that the use of structural design and materials combination to enhance the thermal isolation performance, to reduce the weight and thickness, and to increase the flexibility. So the investigation in this paper is focused on the flexible multilayer thermal insulation material for high/low temperature resistance.

The structure of flexible multilayer insulation material [2]

The evacuated material consists of outer fabric, inner fabric, and middle multilayer insulation systems. The middle multilayer system consists of a large number of highly reflective shields, usually between 6 and 12 micrometers of insulation thickness, separated from

* Corresponding author; e-mail: jinjing_8327@163.com

each other by thin non-conducting spacers. The shields are generally made out of polyester (PET) films (typically 6 to 12 micrometers). For reflecting, the shields are coated with vacuum-deposited aluminum with a thickness between 0.03 and 0.05 micrometers. The common materials for the spacer are polyester netting, and bonding PET films are added to protect the aluminum film and to reduce heat transfer.

Numerical models for thermal analysis

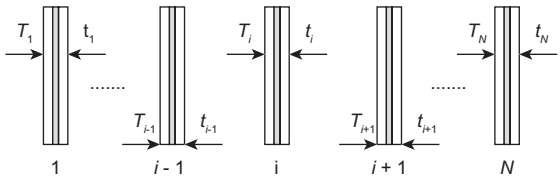

Figure 1. The temperature distribution of the multilayer reflective shields

The heat transfer mechanism of the multilayer insulation material can be extremely complex, and can be modeled using the fractal derivative [3], and the theoretical analysis of thermal insulation for low/high temperature insulation is of economic interest, and a biomimic design of multi-scale materials was reported in [4]. Here, the heat transfer through the middle multilayer system is discussed. The heat transfer through the middle system consists of solid heat transfer, gas transfer and radiation. Figure 1 shows a sketch of the temperature distribution for multilayer reflective shields.

The heat flux through the reflective shields [5]

The reflective shield can be viewed as multi-level wall. So in a steady-state condition the heat flux (Q) through i reflective shields can be written with respect to the dependence of the thermal conductivity of the temperature:

$$Q = \frac{t_i - T_i}{R_f} = \frac{A(t_i - T_i)}{\dfrac{\delta_1 + \delta_3}{c_{\mathrm{Pet}} + d_{\mathrm{Pet}}\left(\dfrac{T_i + t_i}{2}\right)^{e_{\mathrm{Pet}}}} + \dfrac{\delta_2}{c_{\mathrm{Al}} + d_{\mathrm{Al}}\left(\dfrac{T_i + t_i}{2}\right)^{e_{\mathrm{Al}}}}} \tag{1}$$

where R_f is the thermal resistance, δ_1 – the thickness of PET, δ_2 – the thickness of Al, δ_3 – the thickness of PET (bonding layer), and A – the area of the shield. c_{Pet}, d_{Pet}, e_{Pet}, c_{Al}, d_{Al}, e_{Al} are the constants for empirical function of thermal conductivity, T_i and t_i are the boundary temperatures of i reflective shield which can be seen in fig. 1.

The heat flux between the reflective shields in multilayer thermal insulation material

Heat transfer between reflective shields includes solid heat transfer, gas heat transfer and thermal radiation that are in parallel [6]. The solid heat transfer includes heat conduction through spacers and contact heat transfer between spacer and shield that are series. As well as, the gas heat transfer includes gas convection and conduction. Nevertheless the quantity of contact heat transfer between spacer and shield is unpredictable and gas convection is so small that they are neglected.

The solid heat conduction through spacer

Considering the dependence of the thermal conductivity of the temperature for the spacers, the heat flux through space between i-1 shield and i shield can be obtained.

$$Q_s = \left[c_s + d_s \left(\frac{t_{i-1} + T_i}{2} \right)^{e_s} \right] \frac{A_s (T_i - t_{i-1})}{\delta} \tag{2}$$

where Q_s is the heat flux through space between i - 1 shield and i shield, c_s, d_s, e_s are the constants of the spacer, A_s is the area of the spacer, and δ is the thickness of the spacer.

The gas heat transfer between the reflective shields [7]

For the gas heat flux (Q_g) the following formula is valid:

$$Q_g = \frac{A_g (T_i - t_{i-1})}{\delta} \left\{ \left[\alpha \left(\frac{\gamma+1}{\gamma-1} \right) \left(\frac{R}{8\pi M_g \frac{T_i - t_{i-1}}{2}} \right)^{0.5} P\delta \right]^{-1} + \left[\lambda_0 + h \frac{t_{i-1} + T_i}{2} \right]^{-1} \right\}^{-1} \tag{3}$$

where α is the thermal accommodation factor between adjacent reflective shields, γ – the quotient of the specific heats, M_g – the molecular mass of air, R = 8.3145 J/mol – the universal gas constant, P – the pressure between the adjacent reflective shields. For α, the following relation is valid: $\lambda_0 = 7.925 \cdot 10^{-4}$ W/mK, $h = 8.562 \cdot 10^{-5}$W/mK^2; $A_g = A - A_s$.

The radiation heat transfer between the reflective shields [8]

In a high vacuum environment, the heat transfer through reflective shields not touching each other is only radiation heat transfer Q_r. Therefore, the radiation heat flux is the minimum of the heat flux for this multilayer system, which cannot be reached in practical application. But the minimum heat flux can be used as a scale for comparison to a practically realized multilayer insulation system.

For the radiation heat flux between two adjacent reflective shields the following expression is valid, considering the emission of the reflective shields surfaces in a good approximation dependence of the temperature.

$$Q_r = \frac{A_g \sigma (T_i^4 - t_{i-1}^4)}{\frac{1}{a_1 t_{i-1}^{b1}} + \frac{1}{a_2 T_i^{b2}} - 1} \tag{4}$$

where a_1, b_1, a_2, and b_2 are constants for the reflective shields, σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4).

For the total heat flux between two adjacent shields can be expressed:

$$Q = \frac{A_g (T_i - t_{i-1})}{\delta} \left\{ \left[\alpha \left(\frac{\gamma+1}{\gamma-1} \right) \left(\frac{R}{8\pi M_g \frac{T_i - t_{i-1}}{2}} \right)^{0.5} P\delta \right]^{-1} + \left(\lambda_0 + h \frac{t_{i-1} + T_i}{2} \right)^{-1} \right\}^{-1} +$$

$$+ \frac{A_g \sigma (T_i^4 - t_{i-1}^4)}{\frac{1}{a_1 t_{i-1}^{b1}} + \frac{1}{a_2 T_i^{b2}} - 1} + \left[c_s + d_s \left(\frac{t_{i-1} + T_i}{2} \right)^{e_s} \right] \frac{A_s (T_i - t_{i-1})}{\delta} \tag{5}$$

The heat flux through the material, the boundary temperatures, the thickness of the shields and spacers and other parameters can be obtained by the experiments. Then the temperature distribution of the whole material and the solid heat flux, gas heat flux and radiation heat flux through every layer can be estimated by eq. (5). The overall solution scheme of the heat transfer equations is iterative. The temperature distribution of shields can be calculated by Newton iteration and dichotomy method. The solid heat transfer flux, the gas transfer flux and radiation transfer flux between adjacent reflective shields can be calculated by analogy.

Results and discussion

As we mentioned, the calculation does not claim to be able to predict exactly heat transfer values. So the numerical results should only give ideas for improving the insulation quality [9].

The experimental heat fluxes (straight lines) are compared against the estimated heat fluxes which are obtained from numerical model (curves with symbols) in fig. 2, for specimens of 10, 15, 20, 25, 30 layers thermal insulation materials. Overall, in the sense the deviations between the calculated results and the experimental ones are not significant. And the calculated values are a little lower than experimental values. Because there are other heat transfer modes which are neglected in the numerical model through the multilayer materials, this indicates that the numerical model which is presented is this paper turns to be a good representation of the heat flux through the multilayer material.

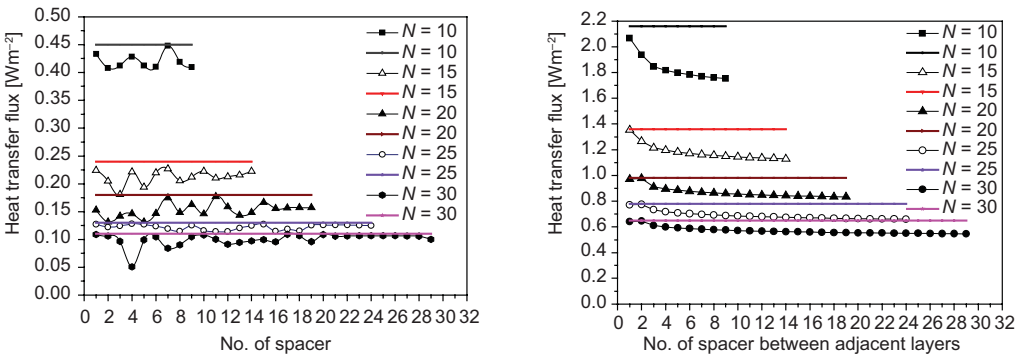

Figure 2. Comparison between calculated values and experimental values from cold temperature (123 K) to normal temperature (273 K) and hot temperature (433 K) to normal temperature
(for color image see journal web site)

Figure 3 shows the temperature distributions of reflective shield with different layers, for specimens with 10, 15, 20, 25, 30 layers of the middle multilayer system. It can be shown that the number of layers (N) has great influence on the temperature distribution in multilayer thermal insulation material. The smaller is the number of the layers, the more acutely the inner temperature varies. The temperature gradient increases with the decrease of the temperature.

It is shown that the solid heat transfer flux decreases while the radiation heat transfer flux increases with the increase of the temperature in fig. 4(a). The gas heat transfer flux is almost the same from layer to layer. So, the solid heat transfer contribution decreases while the radiation contribution increases. The solid heat transfer is the main part approaching the cold temperature (123 K). The radiation heat transfer is the main part approaching the normal temperature (273 K). The gas heat transfer contribution is small from layer to layer.

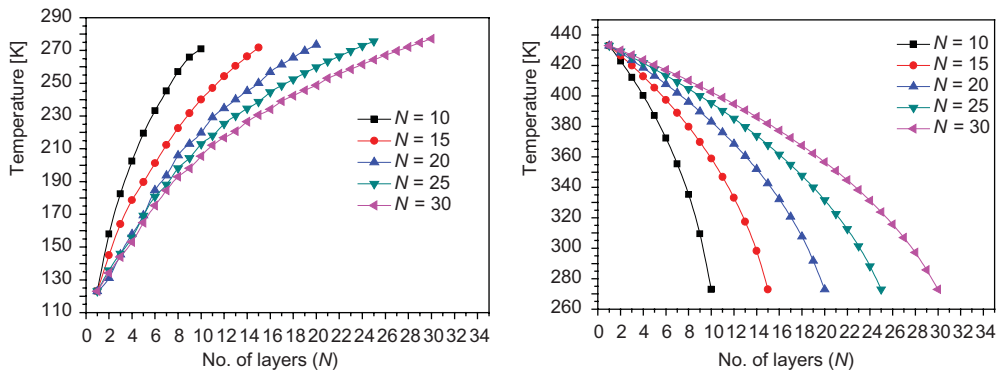

Figure 3. Temperature distributions of reflective shields with different layers from cryogenic temperature (123 K) to normal temperature (273 K) and high temperature (433 K) to normal temperature *(for color image see journal web site)*

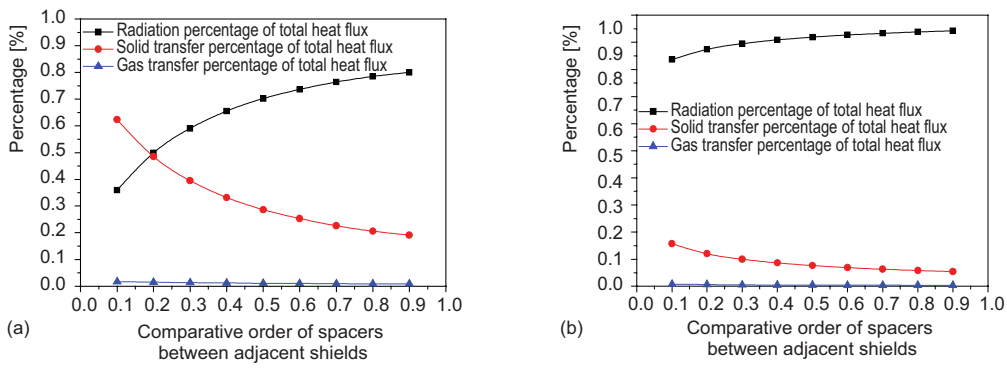

Figure 4. Share of radiation transfer flux, solid transfer flux, and gas transfer flux in total heat transfer between two adjacent shields of 10 layers; (a) from the cold temperature (123 K) to the normal temperature (273 K), (b) from the normal temperature (273 K) to the hot temperature (433 K) *(for color image see journal web site)*

From the normal temperature (273 K) to hot temperature (433 K), the solid heat transfer flux decreases with the increase of the temperature in fig. 4(b). The gas heat transfer flux is small and is almost the same from layer to layer. There is a little increase for the ratio of the radiation heat flux and the radiation heat transfer is the main part between hot temperature and normal temperature.

Conclusions

The errors between experimental heat fluxes and the calculated results by model in this paper are below 10%. Comparing experimental results and theoretical calculations, it is shown that the theoretical calculations are consistent with the measured heat flux trends. So the eq. (5) can be used to process the numerical analysis for the multi-layer insulation materials. However, there are differences between theoretical calculations and experimental results which can be concluded that there is still room for improvement. There are three reasons for the differences as follows. First, the non-uniform structure of material itself and the defects led to the lower theoretical value and it is not uniform. Second, in different temperature environment, there are changes in the thermal conductive behavior of the material, which is the

problem of material itself and measurements. Third, all the scattering and reflection of heat transfer are considered as the thermal resistances in the theoretical estimation.

According to the model for the calculation of temperature distribution and radiation, solid, gas transfer flux from high/low temperature to normal temperature, solid transfer flux decreases while radiation heat transfer flux increases with the increase of the temperature from cold to normal temperature, and radiation transfer is the main part in heat transfer from high to normal temperature. Finally, the model is greatly useful to design and improve the properties of the multilayer material.

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