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A numerical analysis of heat transfer in an evacuated flexible multilayer insulation material

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Abstract In this article, the theoretical heat transfer of flexible multilayer insulation material which can be used in high (<433 K) and low temperature (>123 K) environments has been analyzed. A mathematical model has been developed to describe the heat flux through flexible multilayer insulation material, where the heat transfer consists of thermal radiation, solid spacers and gas heat transfer. The equations for heat transfer model have been solved by iterative method combining with dichotomy method using Matlab. Comparison between the experimental results and the calculated values which are obtained from the model shows that the model is feasible to be applied in practical estimation. The investigation on the flexible multilayer thermal insulation material will present active instruction to improve the performance and accomplish optimum design of the material.

Keywords Flexible multilayer insulation · Heat transfer model · High-low temperature

Introduction

Protection of human is the cause of protective material research, and flexible protective materials are a necessary condition for normal moving in special occasions to explore the world and the universe. Most of the flexible protective materials are starting at the demand for these special occasions. Its basic requirements are light to reduce the burden, flexible to reduce the barriers and energy consumption, easy to move, and protective to all kinds of hot, light, electricity and radiation effects. Overall, the protection in temperature field including cold and hot environments is the most basic part in protection or for human isolation.

The flexible multilayer insulation material is high efficiency on thermal insulation and it is a good choice to form thermal protection materials [1]. And the use of the flexible multilayer material is regarded as one of the most effective means of energy conservation in applications [2].

In order to obtain the protective material with high insulation, the most thing people want to attain and study constantly is that the use of structural design and material combinations to enhance the thermal isolation performance, reduce the weight and thickness and increase the flexibility. The flexible multilayer insulation material has been widely applied in spacecrafts, polar environments, volcano exploration and so on, because of good insulation, light weight and little pollution. The heat transfer mechanism of the multilayer insulation material can be extremely complex [3]. And the analysis of thermal insulation for low and high temperature insulation is of economic interest [4]. So the investigation in this article is focused on the theoretical heat transfer of flexible multilayer thermal insulation material for high–low temperature resistance.

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The structure of the flexible multilayer insulation material

The evacuated flexible multilayer insulation material (Fig. 1), which is discussed in this article, consists of outer

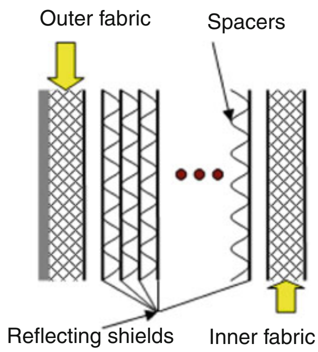

Fig. 1 The structure of the flexible insulation material

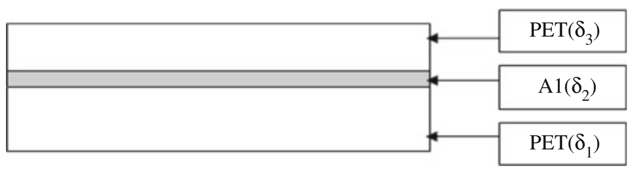

Fig. 2 The sandwich structure of the reflecting shield

fabric, inner fabric and middle multilayer insulation system. To endure high temperature, the outer and inner fabrics are coated with polytetrafluoroethylene (PTFE). And to reduce the heat transfer, the middle multilayer system consists of a large number of highly reflecting shields which is about 14.03 μm, separated from each other by thin nonconducting spacers which is about 2 mm. The common materials for the spacer are polyester netting. The shields are made out of polyester (PET) films (typically 8 μm), which have high mechanical strength and low thermal conductivity. For reflecting, the shields are coated with vacuum-deposited aluminium (Al) (with a thickness of 0.03 μm). And bonding PET films (with a thickness of 6 μm) are added to protect the Al film and reduce heat transfer. Figure 2 shows a sketch of this type of reflecting shield.

Numerical models for thermal analysis

The heat transfer through the middle multilayer system consists of solid heat transfer, gas transfer and radiation. Heat transfer through the super-insulation normal to the shield surfaces then is predominantly by radiation exchanges between the shields [5]. A second heat loss mechanism in multilayer insulation is by solid heat transfer parallel to the surfaces of shields and spacers. The third is the gas transfer between shields which is relatively little [6]. Figure 3 shows a sketch of the temperature distribution for multilayer reflecting shields.

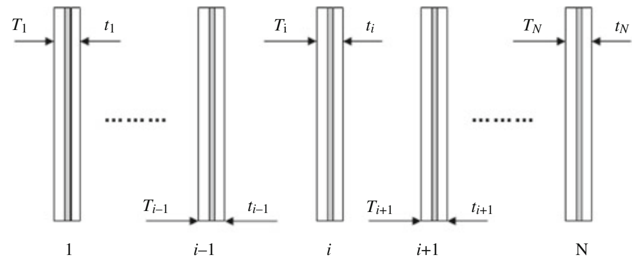

Fig. 3 The temperature distribution of the multilayer reflecting shields

The calculation of heat transfer through middle multilayer system does not claim to be able to predict exactly heat fluxes. Due to some unpredictable changes in parameters such as pressure between adjacent reflecting shields, uniform contact pressure and gas pressure. The following calculations are appropriate to present an idea for the contributions of different heat transfer modes to improve the insulation quality [7].

The heat flux through the reflecting shield

The structure of the reflecting shield can be seen in Fig. 2. And the reflecting shield can be viewed as multi-level wall. So in a steady-state condition the thermal resistance ($R_{f,i}$) of the reflecting shield can be written.

$$R_{f,i} = \frac{1}{A}\left(\frac{\delta 1 + \delta 3}{\lambda_{\mathrm{PET}}, i} + \frac{\delta 2}{\lambda_{\mathrm{Al},i}}\right) \quad (1)$$

where δ_1 is the thickness of PET, δ_2 is the thickness of Al, δ_3 is the thickness of PET (bonding layer), $\lambda_{\mathrm{PET},\ i}$ is the thermal conductivity of PET for i shield and $\lambda_{\mathrm{Al},\ i}$ is the thermal conductivity of Al for i shield, and A is the area of the reflecting shield.

For the dependence of the thermal conductivity of the temperature, the following empirical function is suggested [8].

$$\lambda = c + \mathrm{d}T^{e} \quad (2)$$

where c, d, e is the constant for empirical function.

Therefore, the thermal conductivity of the PET film and Al film can be obtained as following.

$$\lambda_{\mathrm{PET},i} = c_{\mathrm{PET}} + d_{\mathrm{PET}}\left(\frac{T_i + t_i}{2}\right)^{e_{\mathrm{PET}}} \quad (3)$$

$$\lambda_{\mathrm{Al},i} = c_{\mathrm{Al}} + d_{\mathrm{Al}}\left(\frac{T_i + t_i}{2}\right)^{e_{\mathrm{Al}}} \quad (4)$$

where, c_{PET}, d_{PET}, e_{PET} are the constants of the PET shield, c_{Al}, d_{Al}, e_{Al} are the constants of the Al-flim, T_i and t_i are the boundary temperatures of i reflecting shield which can be seen in Fig. 3.

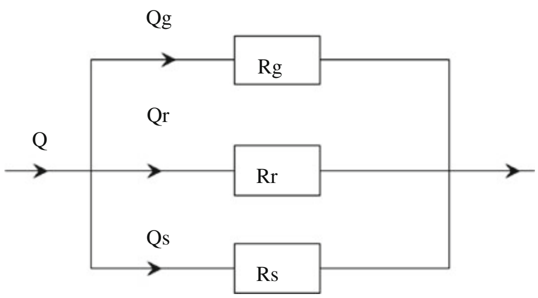

Fig. 4 Heat transfer mechanisms between adjacent reflecting shields

So, the heat flux through i reflecting shield is given.

$$Q_i = \frac{t_i - T_i}{R_{f,i}} = \frac{A(t_i - T_i)}{\frac{\delta 1 + \delta 3}{c_{PET} + d_{PET}\left(\frac{T_i + t_i}{2}\right)^{e_{PET}}} + \frac{\delta 2}{c_{Al} + d_{Al}\left(\frac{T_i + t_i}{2}\right)^{e_{Al}}}} \quad (5)$$

The heat flux between adjacent reflecting shields in multilayer insulation material

Heat transfer between reflecting shields in multilayer insulation material includes solid heat transfer, gas heat transfer and thermal radiation heat transfer that are in parallel (Fig. 4; [9]). The solid heat transfer includes the 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 the contact heat transfer between spacer and shield is unpredictable and the gas natural convection is so small that they are neglected in the calculation.

The solid heat conduction through spacer

For the dependence of the thermal conductivity of the temperature as above, the thermal conductivity of the spacer ($\lambda_{s,\ i\sim i-1}$) can be written.

$$\lambda_{s,i\sim i-1} = c_s + d_s\left(\frac{t_{i-1} + T_i}{2}\right)^{e_s} \quad (6)$$

Then, the heat flux through space between $i-1$ shield and i shield can be got.

$$Q_{s,i\sim i-1} = \left(c_s + d_s\left(\frac{t_{i-1} + T_i}{2}\right)^{e_s}\right)A_s(T_i - t_{i-1})/\delta \quad (7)$$

where $Q_{s,\ i\sim i-1}$ 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. δ is the thickness of the spacer.

The gas heat transfer between adjacent reflecting shields

For the mean thermal conductivity ($\lambda_{g,\ i\sim i-1}$) of the gas between the adjacent reflecting shields, the following expression which is valid over the whole pressure range can be used.

$$\lambda_{g,i\sim i-1} = \frac{1}{\frac{1}{\lambda_{g,1}} + \frac{1}{\lambda_{g,2}}} \quad (8)$$

where, $\lambda_{g,\ 1}$ is the mean thermal conductivity for free molecules, $\lambda_{g,\ 2}$ the thermal conductivity of the gas at pressure near 10^5 Pa.

For $\lambda_{g,\ 1}$, the following relation is valid.

$$\lambda_{g,1} = \alpha\left(\frac{\gamma + 1}{\gamma - 1}\right)\left(\frac{R}{8\pi M_g \frac{T_i - t_{i-1}}{2}}\right)^{0.5} P\delta \quad (9)$$

where, α is the thermal accommodation factor between adjacent reflecting shields, γ the quotient of the specific heats, M_g the molecular mass of air, $R = 8.3145$ J/mol K the universal gas constant, and P the pressure between the adjacent reflecting shields. For α, the following relation is valid.

$$\alpha = \left(\frac{1}{(A - B)\exp\left(\frac{-0.25(t_{i-1} - 77)}{77}\right) + B} + \frac{1}{(A - B)\exp\left(\frac{-0.25(T_i - 77)}{77}\right) + B} - 1\right)^{-1} \quad (10)$$

where $A = \frac{M_g}{2.3 + M_g}$, $B = \frac{2.4u}{(1+u)^2}$, $u = \frac{M_g}{M_s}$; is the gas viscosity; and M_s the molecular mass of Al.

$\lambda_{g,\ 2}$ is linear depending from the temperature. For the mean thermal conductivity between two temperatures therefore one obtains:

$$\lambda_{g,2} = \lambda_0 + h\frac{t_{i-1} + T_i}{2} \quad (11)$$

where $\lambda_0 = 7.925 \times 10^{-4}$ w/mk, $h = 8.562 \times 10^{-5}$w/mk^2.

In Eq. 8, $\lambda_{g,\ 1}$ is replaced by Eq. 9, and $\lambda_{g,\ 2}$ is replaced by Eq. 11, whereby the mean thermal conductivity of the gas can be expressed as a function of the boundary temperatures, pressure and the distance of the adjacent reflecting shields.

$$\lambda_{g,i\sim i-1} = \left(\left(\alpha\left(\frac{\gamma + 1}{\gamma - 1}\right)\left(\frac{R}{8\pi M_g \frac{T_i - t_{i-1}}{2}}\right)^{0.5} P\delta\right)^{-1} + \left(\lambda_0 + h\frac{t_{i-1} + T_i}{2}\right)^{-1}\right)^{-1} \quad (12)$$

For the gas heat flux ($Q_{g,\ i\sim i-1}$) the following formula is valid.

$$Q_{g,i\sim i-1} = \frac{A_g(T_i - t_{i-1})}{\delta}\left(\left(\alpha\left(\frac{\gamma + 1}{\gamma - 1}\right)\left(\frac{R}{8\pi M_g \frac{T_i - t_{i-1}}{2}}\right)^{0.5} P\delta\right)^{-1} + \left(\lambda_0 + h\frac{t_{i-1} + T_i}{2}\right)^{-1}\right)^{-1} \quad (13)$$

where $A_g = A - A_s$.

The radiation heat transfer between adjacent reflecting shields [10]

In a high vacuum environment, the heat transfer through these reflecting shields not touching each other is only radiation heat transfer (Qr). Therefore, this is of great interest. The radiation heat flux is the minimum of the heat flux for this multilayer insulation 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.

The emission ε of the reflecting shields surfaces in a good approximation dependence of the temperature can be assumed as follows.

$$\varepsilon = aT^b \tag{14}$$

where a, b are constants for an specific material. For the aluminized PET film, then the following values are reached: $a = 0.0051$, $b = 0.248$ [11].

For the distance between adjacent parallel reflecting shields is small, the effective emissivity $\varepsilon_{i\sim i-1}$ can be obtained through Eq. 15.

$$\varepsilon_{i\sim i-1} = \frac{1}{\frac{1}{at_{i-1}^b} + \frac{1}{aT_i^b} - 1} \tag{15}$$

For the radiation heat flux between two adjacent reflecting shields the following expression is valid.

$$Q_{\mathrm{r},i\sim i-1} = \frac{A_{\mathrm{g}}\sigma(T_i^4 - t_i - 1^4)}{\frac{1}{at_{i-1}^b} + \frac{1}{aT_i^b} - 1} \tag{16}$$

For the total heat flux between two adjacent shields following expression is valid.

$$Q_{i\sim i-1} = Q_{\mathrm{s},i\sim i-1} + Q_{\mathrm{g},i\sim i-1} + Q_{\mathrm{r},i\sim i-1} \tag{17}$$

In Eq. 17, $Q_{\mathrm{s},\ i\sim i-1}$ is replaced by Eq. 7, $Q_{\mathrm{g},\ i\sim i-1}$ is replaced by Eq. 13 and $Q_{\mathrm{r},\ i\sim i-1}$ is replaced by Eq. 16, whereby the total heat flux between adjacent shields can be expressed as follows.

$$\begin{aligned} Q_{i\sim i-1} = &\frac{A_{\mathrm{g}}(T_i - t_{i-1})}{\delta}\left(\left(\alpha\left(\frac{\gamma+1}{\gamma-1}\right)\left(\frac{R}{8\pi M_{\mathrm{g}}\frac{T_i - t_{i-1}}{2}}\right)^{0.5} P\delta\right)^{-1}\right. \\ &+ \left.\left(\lambda_0 + h\frac{t_{i-1} + T_i}{2}\right)^{-1}\right)^{-1} + \frac{A_{\mathrm{g}}\sigma(T_i^4 - t_{i-1}^4)}{\frac{1}{at_{i-1}^b} + \frac{1}{aT_i^b} - 1} \\ &+ \left(cs + ds\left(\frac{t_{i-1} + T_i}{2}\right)^{e_s}\right)A_{\mathrm{s}}(T_i - t_{i-1})/\delta \end{aligned} \tag{18}$$

In a steady-state condition, the heat transfer through the whole system (Q_{tot}), through each reflecting shield (Q_i), from layer to layer ($Q_{i\sim i-1}$) remains constant. Then the following equations can be written.

$$Q_{\mathrm{tot}} = Q_i = Q_{i,i-1} \tag{19}$$

Numerical approach

The heat flux through the material (Q_0), the boundary temperatures (x, y), and the thickness of reflecting 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. 18.

The overall solution scheme of the heat transfer equations is iterative [12]. First, the temperature distribution for the multilayer insulation material of ideal model is calculated, and temperature distribution of solid conductive model is also calculated. As T_1 which is equal to x (the low boundary temperature) is known, t_1 can be got by Eq. 5, and T_2 can be calculated by dichotomy method. Then t_N can be obtained by iterative calculation. Contrast t_N and y (the high boundary temperature). If the absolute value of t_N minus y is greater than the given accuracy, change $Q_{i\sim i-1}$ by Eq. 18, and re-calculate the temperature distribution until the absolute value of the two achieve a given accuracy. At last, the solid heat transfer flux, the gas transfer flux and radiation transfer flux between each adjacent reflecting shield can be calculated by analogy.

The comparisons between theoretical calculations and experimental measurements

As mentioned above the presented calculation here does not claim to be able to predict heat transfer values exactly in practical estimation. But the numerical results can give ideas and instructions for improving the insulation quality [13].

The thermal conductivity

In order to determine the accuracy of the heat transfer model, the thermal conductivity is calculated by the heat transfer model and measured by the KES-F7 thermal labo II apparatus at room temperature. For experiments, the temperature of hot plate is 27 °C, and the temperature of cold plate is 17 °C [14]; that is the same as the hot and cold boundary temperatures in the theoretical calculations. The multilayer material evacuated is made of reflecting shields, separated from each other by thin PET nets. The thermal conductivity with different layers of reflecting shields can be seen in Fig. 5.

When the boundary temperature is 27 and 17 °C, the thermal conductivity by theoretical calculation of the

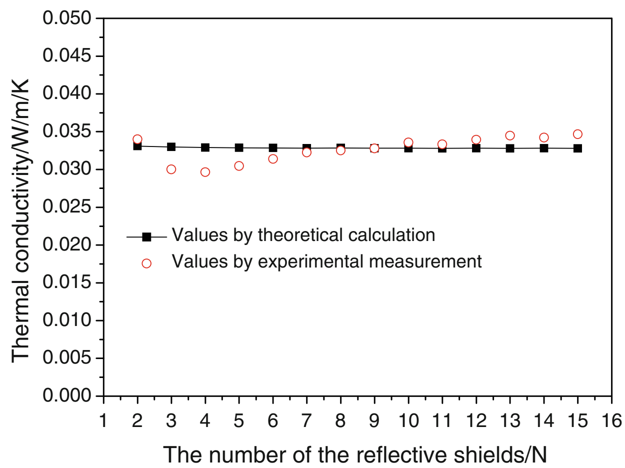

Fig. 5 The thermal conductivity by theoretical calculation and experimental measurements for the material with different reflecting shield layers

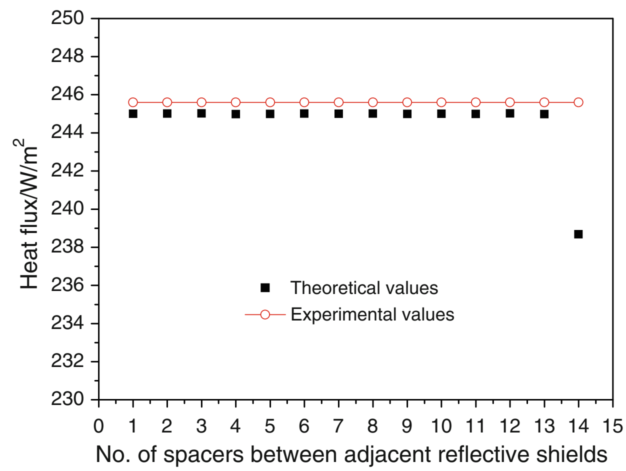

Fig. 6 The comparison of heat fluxes through adjacent reflecting shields between theoretical values and experimental values from low temperature to normal temperature

material is about 0.033 W/mK, and the values which are obtained by experimental measurements fluctuate around the theoretical values. And the difference between theoretical calculation and experimental measures is small. The error for theoretical calculation of thermal conductivity is less than 10%, so the heat transfer model which is developed in this article can be used to analyze the heat transfer for the multilayer insulation materials.

The heat flux between adjacent reflecting shields between high (433 K)–low (123 K) temperature and normal (273 K) temperature

The flexible multilayer insulation material discussed in this article is used in the application at low temperature (123 K)–high temperature (433 K) environment. So the heat fluxes between adjacent reflecting shields from low temperature (123 K)–high temperature (433 K) to normal temperature (273 K) are calculated. And corresponding heat fluxes through experimental measurements are compared with the theoretical values. On the one hand, the degree of consistency between the heat transfer model and experimental results can be obtained. On the other hand, the theoretical calculations can be used to improve the performance of multilayer insulation material. The material consists of reflecting shields with 15 layers and spacers which are added between adjacent reflecting shields. From cold to hot side, the spacers between adjacent reflecting shields followed by No. 1–14. The heat fluxes by theoretical calculations and experimental measurements from high-temperature (433 K) to room temperature (273 K), from low temperature (123 K) to room temperature (273 K) can be seen in Figs. 6 and 7.

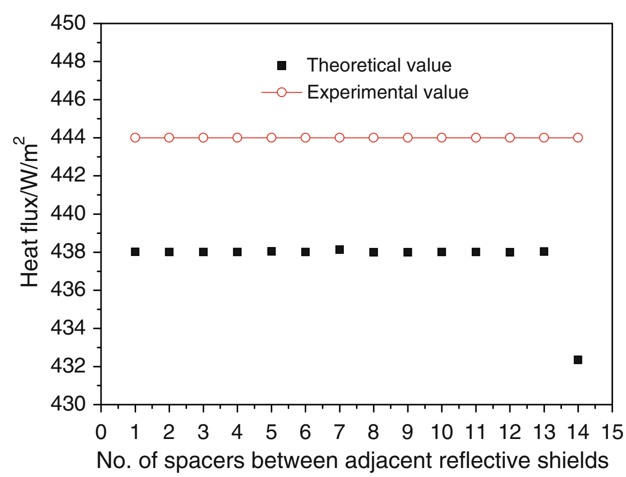

Fig. 7 The comparison of heat fluxes through adjacent reflecting shields between theoretical values and experimental values from high temperature to normal temperature

From low temperature to normal temperature, the heat fluxes which are obtained by experiments through all adjacent reflecting shields are the same and the value is 245.6 W/m^2. And the heat fluxes which are obtained by theoretical calculation are not equal from 238.7 to 245.1 W/m^2. It can be seen that the theoretical calculated values of the heat fluxes are less than the actual measured ones. But actually there is little difference. The maximum error for theoretical heat flux calculation is less than 3%, which is indicating that the theoretical calculations and the actual measured values coincide.

Between high temperature and normal temperature, the heat fluxes which are obtained by experiments through all adjacent reflecting shields are 444.1 W/m^2. The theoretical heat fluxes are between 432.4 and 438.1 W/m^2. And the same as above, the theoretical calculated values of the heat fluxes are less than the actual measured ones. The maximum error for heat flux calculation is also less than 3%, which can be seen that the theoretical calculations and the actual measured values coincide too.

Overall, in the sense the deviations between the calculated results and the experimental ones are not significant. There is a consistent large error between experimental and theoretical heat fluxes through the largest number of spacers. This is mainly caused by the boundary conditions in the process of iterative calculation. The theoretical values of heat flux are solved by iterative method from cold to hot sides. And the heat fluxes through the largest number of spacers are affected by the errors of heat fluxes through spacers from 1 to 13. In addition, the calculated values are a little lower than the experimental values.

Brief summary

The Eq. 18 can be used to process the numerical analysis for the multi-layer insulation materials and the numerical model of the flexible multilayer materials can be applied to practical engineering.

Conclusions

Comparing the experimental results and theoretical calculations, it is shown that the theoretical calculations are consistent with the measured ones. Between 27 and 17 °C, the errors between experimental thermal conductivity and the theoretical results obtained by heat transfer model are less than 10%. And errors between experimental heat fluxes and the calculated results by model in this article are below 3%.

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 the material and the defects led to the lower theoretical heat flux and it is not uniform. Second, in different temperature environments, there are changes in the thermal conductive behaviour of the material, which is the problem of the material and measurements. Third, all the scattering and reflection of heat transfer are considered as the thermal resistances in the theoretical estimation. The multilayer structure and the return of heat transfer through actual measurements lead to the reduction of the heat resistances. So, the actual heat flux is greater than the theoretical calculation of the heat flux.

Above all, the numerical model of the flexible multilayer material can be applied in practical estimation. And the model is greatly useful to design and improve the properties of the flexible multilayer thermal insulation material.

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