Influence of multilayer heat insulation material on infrared feature of a satellite

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Abstract: As to the deficiency of ignoring multilayer heat insulation material or simply taking its heat transfer process equivalently as the thermal insulation steady state process in infrared characterization research of spatial targets, the factual heat transference ways of multilayer heat insulation material were considered and the temperature calculation models of multilayer heat insulation material′s radiation heat transfer, solid thermal conduction and residual gas thermal conduction were established. On the base of the models, the influence of different heat transference ways of multilayer heat insulation material on a satellite′s surface temperature and infrared feature in 3–6 μm band and in 6–16 μm band was calculated and analyzed. The calculation results show different heat transference ways of multilayer heat insulation material have more influence on the satellite′s infrared feature in 6–16 μm band than in 3–6 μm band. The research result has referential value for improving infrared feature calculation precision of spatial targets.

Key words: multilayer heat insulation material; earth satellite; temperature field; infrared feature
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多层隔热材料对卫星红外特性的影响

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摘 要: 针对空间目标红外特性研究中，忽略多层隔热材料的影响或将其传热过程等效于绝热稳态过程的不足,考虑多层隔热材料中的实际传热方式,分别建立了卫星表面多层隔热材料中辐射换热、间隔层固体导热和残留气体导热的温度计算模型；根据模型计算分析了卫星表面多层隔热材料中不同传热方式对自身表面温度及 3~6 μm 和 6~16 μm 两个波段红外辐射特性的影响；结果显示多层隔热材料中不同传热方式对卫星长波红外辐射特性的影响大于中波红外辐射特性，文中对于提高空间目标红外辐射特性的计算精度具有参考价值。

关键词: 多层隔热材料； 地球卫星； 温度场； 红外特性

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0 Introduction

Multilayer heat insulation material has good heat-shielding performance. Thus more and more multilayer heat insulation material has been used for heat insulation of spatial targets[1-4]. As to the deficiency of ignoring the multilayer insulation material or simply taking its heat transfer process equivalently as the thermal insulation steady state process in spatial targets' infrared feature research literatures, this paper has built up theoretical calculation models of multiple heat transfer modes of multilayer heat insulation material and analyzed the influence of multilayer heat insulation material's radiation heat transfer, solid thermal conduction and residual gas thermal conduction on the surface temperature and the infrared radiation feature of a satellite in detail.

1 Heat transference model of multilayer heat insulation material

The factual heat transference ways of multilayer heat insulation material are mainly consisted of radiation heat transfer, solid thermal conduction and residual gas thermal conduction[5-7], as shown in Fig.1.

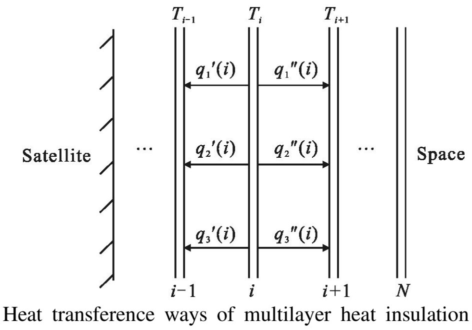


Fig.1 Heat transference ways of multilayer heat insulation material

The heat density $q_1'(i)$ and $q_1''(i)$ of radiation heat transfer are obtained by Eq. (1), where n, a, s are refraction coefficient, absorption coefficient, dissipation coefficient of septum layer, δ is thickness of septum layer, ε is emissivity of inner reflection layers' surfaces.

$$q_1'(i)=\frac{n^2\sigma(T_i^4-T_{i-1}^4)}{\left(\frac{2}{\varepsilon}-1\right)+(a+2s)\frac{\delta}{2}},$$

$$q_1''(i)=\frac{n^2\sigma(T_i^4-T_{i+1}^4)}{\left(\frac{2}{\varepsilon}-1\right)+(a+2s)\frac{\delta}{2}} \tag{1}$$

The heat density $q_2'(i)$ and $q_2''(i)$ of solid thermal conduction are obtained by Eq.(2), where K_s is solid heat diffusivity and its value is δ/R_s. R_s is entire thermal resistance of solid thermal conduction.

$$q_2'(i)=K_s\frac{n^2\sigma(T_i-T_{i-1})}{\delta},\ q_2''(i)=K_s\frac{n^2\sigma(T_i-T_{i+1})}{\delta} \tag{2}$$

The heat density $q_3'(i)$ and $q_3''(i)$ of residual gas thermal conduction are obtained by Eq.(3), where a_l is total thermal accommodation coefficient of residual gas molecular, γ is gas specific heat ratio, R_m is Universality gas factor, M is gas molecular weight, is gas pressure. P is gas temperature.

$$q_3'(i)=\frac{\gamma+1}{\gamma-1}a_l\sqrt{\frac{R_m}{8\pi M}}\frac{P}{\sqrt{T}}(T_i-T_{i-1}),$$

$$q_3''(i)=\frac{\gamma+1}{\gamma-1}a_l\sqrt{\frac{R_m}{8\pi M}}\frac{P}{\sqrt{T}}(T_i-T_{i+1}) \tag{3}$$

The heat transfer model of the reflection layer ($i=1$) which faces to the satellite of multilayer heat insulation material is obtained by Eq.(4), where ρ, c and Δd are density, specific heat capacity and thickness of reflection layers.

$$q_1''(1)+q_2''(1)+q_3''(1)+q_1'(1)+\rho c\Delta d\frac{\mathrm{d}T_1}{\mathrm{d}\tau}=0 \tag{4}$$

The heat transfer model of the reflection layers ($i=1, \cdots, N-1$) of multilayer heat insulation material is obtained by Eq.(5).

$$q_1''(i)+q_2''(i)+q_3''(i)+q_1'(i)+q_2'(i)+q_3'(i)+\rho c\Delta d\frac{\mathrm{d}T_i}{\mathrm{d}\tau}=0 \tag{5}$$

The heat transfer model of the reflection layer ($i=N$) which faces to the space is obtained by Eq.(6), where α' and ε' are solar radiation absorptivity and infrared emissivity of outer reflection layer's surface facing to the space. E_S, E_{SE} and E_E are solar heat flux, earth albedo heat flux and earth heat flux, which the layer gets.

$$q_1'(N)+q_2'(N)+q_3'(N)+\rho c\Delta d\frac{\mathrm{d}T_i}{\mathrm{d}\tau}=\alpha' E_S+\alpha' E_{SE}+\varepsilon' E_E-\varepsilon'\sigma T_N^4 \tag{6}$$

2 Numerical results and discussions

The research object is a three-axis stabilized satellite in the sun-synchronous orbit. It has six surfaces. $\pm y$ surfaces are radiating surfaces and the others are covered with the multilayer heat insulation material. $+x$ surface points to motion direction of the satellite and $+z$ surface points to geocenter. The satellite orbit period is divided into 600 intervals. The orbit parameters, the physical parameters and the spatial heat flux of the satellite can be obtained from the literature[8]. The reflection layers of multilayer heat insulation material are aluminum foil and their physical parameters are: ρ=2 710 kg/m^3, c=902 J/(kg·K), Δd=10 μm, N=20, ε=0.05, α'=0.41, ε'=0.68. The septum layers are fibrous glass and the physical parameters are: n=1, a=1.3×10^3 m^{-1}, s=2.6×10^4 m^{-1}, δ=76 μm. Other physical parameters of the multilayer heat insulation material are: K_s=6.25×10^6 W/(m·K), a_l=0.818, γ=1.4, R_m=8 314 N·m/kmol, M=29.

In Fig.2(a) is the surface temperature of satellite's body of which the heat transference model of multilayer heat insulation material includes radiation heat transfer, solid thermal conduction and residual gas thermal conduction. Fig.2(b) is the temperature difference between taking the heat transference model in this paper and taking the heat transfer process equivalently as the thermal insulation steady state process. As shown in Fig.2, consideration the factual heat transference ways of multilayer heat insulation material has influence on the temperature of surfaces of satellite's body which are covered with the multilayer heat insulation material. Temperature differences of $-z$ surface and $-x$ surface are greater than the others and $-z$ surface has the greatest temperature difference. $-z$ surface always faces to space, so it only gets solar heat flux in the sunshine and no heat flux in the earth's shadow. The thermal boundary condition of $-z$ surface has greater change than others, so the influence on its heat transference model of multilayer heat insulation material is greater than others.

In Fig.3, taking the satellite's body as grey body, (a) and (c) are infrared radiant exitances of satellite's body of which the heat transference model of multilayer heat insulation material includes three heat transference ways in this paper in 3–6 μm band and 6–16 μm band, the infrared radiant exitances include the satellite's body thermal radiation and the reflective radiation of solar heat flux, earth albedo heat flux and earth heat flux. Fig.3(b) and (d) are radiant exitance

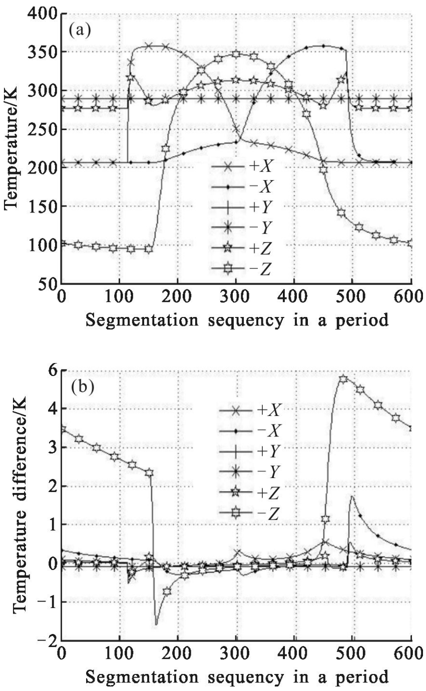
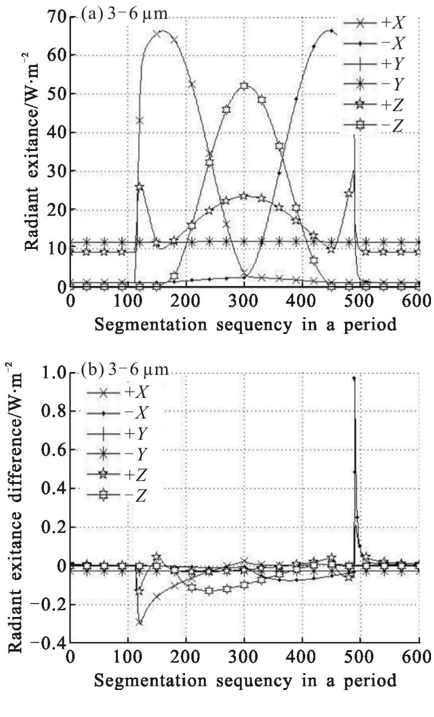


Fig.2 Surface temperature and temperature difference of satellite's body



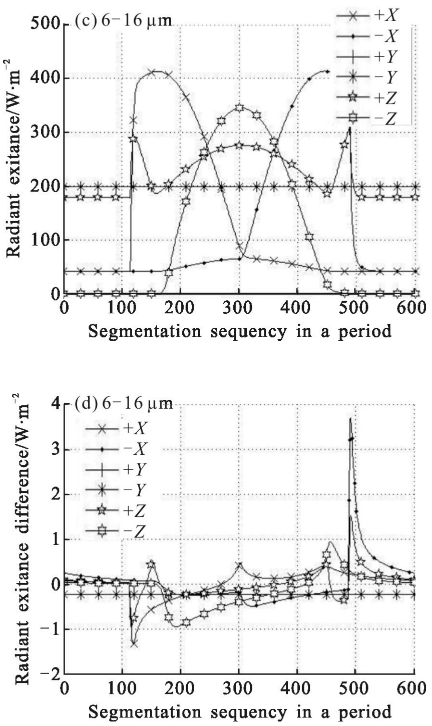
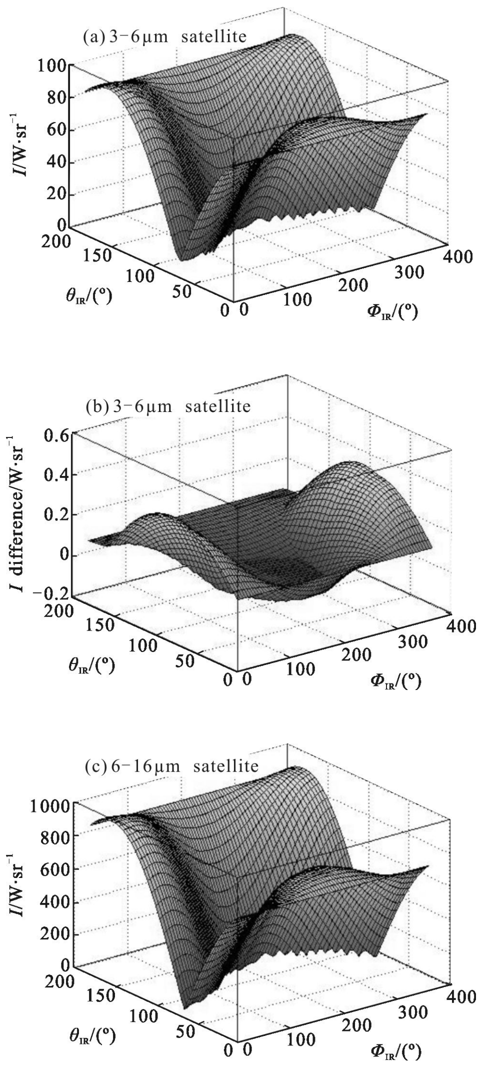


Fig.3 Radiant exitances and radiant exitance differences of satellite's body in two IR bands

differences in two IR bands. As shown in (b) and (d) of Fig.3, one can find $-x$ surface has greater radiant exitance differences than $-z$ surface, although $-z$ surface has the greatest temperature difference. This is because the temperature of $-z$ surface is low when its temperature difference changes rapidly and its radiant exitance changing is small which is caused by its temperature changing. In addition, the radiant exitance difference in 6–16 μm band is greater than the one in 3–6 μm band. This is because most infrared radiant energy of satellite's body surfaces caused by their temperature is concentrates in 6–16 μm band.

In Fig.4, (a) is the spatial distribution of radiant intensity in 3–6μm band of the satellite at the 490th interval of the orbit period. As shown in (b), the greatest radiant intensity difference in 3–6 μm band is 0.324 4 W/sr. (c) is the spatial distribution of radiant intensity in 6–16 μm band at the 492 th interval. The greatest radiant intensity difference in 6–16 μm band is 1.2693W/sr which is shown in (d). By comparing (b) and (d) in Fig.3 with ones in Fig.4, one can find the heat transference model of multilayer heat insulation material including three heat transference ways in this paper has much more influence in radiant exitance of satellite's body than on radiant intensity of satellite. The main reason is that radiant intensity of satellite is related to the area of satellite's body and solar panel. And the area of solar panel which is not covered with the multilayer heat insulation material is much more than the one of satellite's body which is covered with the multilayer heat insulation material, so radiant intensity of satellite's body has less effect on overall radiant intensity of satellite. If spatial targets have much more area which is covered with the multilayer heat insulation material, the influence of the material on their infrared radiant intensities should be analyzed.



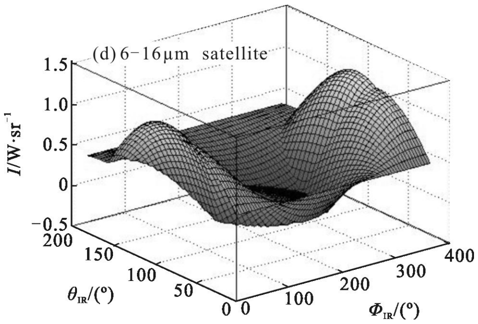


Fig.4 Radiant intensities differences of satellite

3 Conclusions

Theoretical calculation models of multiple heat transfer modes of multilayer heat insulation material are built up. One can find that multilayer heat insulation material′ s radiation heat transfer, solid thermal conduction and residual gas thermal conduction have influence on the surface temperature and infrared feature of the satellite in 3–6 μm band and in 6–16 μm band. The influence on the infrared feature in 6–16 μm band is more distinct than in 3–6 μm band. So in the calculation of spatial targets′ infrared feature, the influence which is caused by multiple heat transfer modes of multilayer heat insulation material should be analyzed.

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