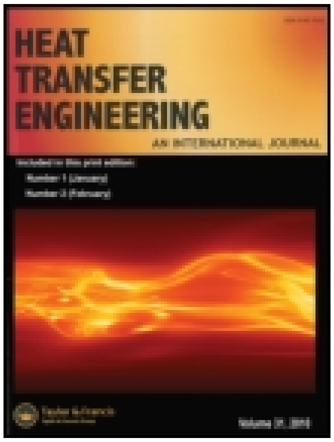

Heat Transfer Engineering
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uhte20

Heat Transfer Characteristics of an Innovative Thermal Protection System Based on Photonic Crystals

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Accepted author version posted online: 02 Sep 2013.Published online: 25 Nov 2013.

To cite this article: Hao-Chun Zhang , Xun Ben , Yao Li & Yang-Yu Guo (2014) Heat Transfer Characteristics of an Innovative Thermal Protection System Based on Photonic Crystals, Heat Transfer Engineering, 35:6-8, 583-588, DOI: 10.1080/01457632.2013.837641

To link to this article: http://dx.doi.org/10.1080/01457632.2013.837641

Heat Transfer Engineering, 35(6–8):583–588, 2014

ISSN: 0145-7632 print / 1521-0537 online
DOI: 10.1080/01457632.2013.837641

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Heat Transfer Characteristics of an Innovative Thermal Protection System Based on Photonic Crystals

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In order to protect the internal components of an aircraft from the damage caused by high temperature and heat flux, an effective thermal protection structure must be designed and developed. In this paper, heat transfer characteristics for an innovative thermal protection coating structure are investigated, based on three-dimensional photonic crystals (SiC-3D PCs). The actual system with coating material, containing photonic crystals, is simplified as a macroscopic model of one-dimensional coupled conduction–radiation heat transfer among three layers composed of semitransparent media. Moreover, according to preliminary physical parameters, heat transfer profiles and thermal protection efficiency for the whole system are estimated. In addition, the effect of the photonic crystals part is analyzed.

INTRODUCTION

With the flight speed and flying time of aircraft increasing, the accumulation of the aerodynamic heat means aircraft surfaces are faced with enduring high temperature between 873 K and 1473 K [1]. In order to protect the internal components and parts of the aircraft from damage from the high temperature and the heat flux, it is necessary to design and develop an effective thermal protection structure for the aircraft. The conventional thermal protection approaches make use of ablation materials or thermal insulation ceramics. However, from the actual application and the accidents that have taken place [2], the repeatability and reliability of these approaches are now constantly questioned by researchers.

Yablonovitch [3] and John [4] individually and independently in 1987 proposed the concept of photonic crystals (PCs), which exhibited a new kind of approach to make a material have both high reflectivity and high emissivity. Such kinds of material can be constructed by utilization of an ordered structure. With a reasonable structure manufacture, it is possible for the material to obtain both higher reflectivity and higher emissivity at the infrared band of the spectrum, by using the thermal protection coating made from three-dimensional (3D) photonic crystals thin films.

Noda et al. [5] prepared the GaAs 3D photonic crystals at the infrared bandgap by a stacking method, in which the reflectivity over wavelengths 0.9–1.6 μm was larger than 80%, and the reflectivity was close to 100% for wavelengths 1.3–1.55 μm. Chen et al. [6] made one-dimensional (1D) photonic crystals by using silicon slices, which had an excellent reflectivity between 1.4 and 1.7 μm. In fact, more investigations have been focused on the reflectivity of photonic crystals at the middle infrared band. Pralle et al. [7] declared that a certain kind of two-dimensional (2D) photonic crystals made from silicon slices had reflectivity larger than 90% on average for wavelengths 3.7–14 μm. Wang et al. [8] had made 1D photonic crystals on the silicon slice by electrochemical corrosion, and the experimental results indicated that the reflectivity was approaching 100% for wavelengths 2.5–3.5 μm. However, although many kinds of photonic crystals have been developed, heat transfer mechanism and characteristics for thermal protection structure based on photonic crystals need to be addressed.

In this paper, heat transfer characteristics of an innovative thermal protection system based on 3D PCs (SiC-3D PCs) are discussed. Based on an actual system with coating material containing photonic crystals, a macroscopic model of one-dimensional coupled conduction–radiation heat transfer in three layers composed by semitransparent media is established. Further, according to preliminary physical parameters, back response temperature of the substrate to the heating from

This work is supported by the National Natural Science Foundation (51006026, 90916020, 50930007) and the Fundamental Research Funds for the Central Universities (grant HIT.NSRIF.2012.072).

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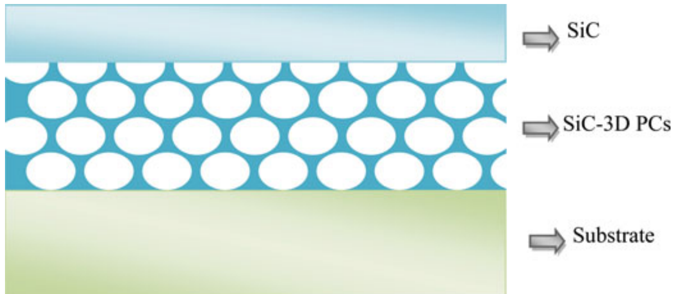

Figure 1 Overview of the new thermal protection structure by SiC-3D PCs. (Color figure available online.)

external flow field under two conditions is discussed, with photonic crystals coating and without photonic crystals coating in the structure. In addition, the comprehensive thermal protection characteristic of the current structure is analyzed, with considerations of factors such as reflection, radiation, and heat transfer process.

STRUCTURE AND PHYSICAL MODEL

The new 3D photonic crystals thermal protection coating structure is designed to be fabricated in such a way that the outermost layer is the SiC and the internal layer is 3D photonic crystals made from YSZ or SiC, which will make up the structure SiC-3D PCs. Within the structure, the SiC layer is the radiation coating, and the photonic crystals layer separates the substrate from the heat transferred inside the SiC layer. Therefore, as shown in Figure 1, the structure has a double effect of radiative thermal protection and reflective thermal protection.

As shown in Figure 2, the composite plate is composed of three layers of absorbing, emissive, and scattering media, which sequentially correspond to the SiC layer, the PCs layer, and the substrate layer, from the left side to the right side. Among the three layers, both the optical characteristics and thermophysical characteristics are different. In addition, the composite plate is located between two black surfaces $S_{-\infty}$ and $S_{+\infty}$, which stand for the surroundings, and their temperatures are denoted respectively by $T_{-\infty}$ and $T_{+\infty}$. In addition, the surrounding fluid temperatures and the convective heat transfer coefficients are denoted by T_{g1}, T_{g2}, h_1, and h_2, respectively.

The selective media absorption coefficient κ_b, absorption coefficient α_b, scattering coefficient $\sigma_{s,b}$, refractive index n_b, and the reflectivity ρ_b varying with the wavelength are approximated by a set of rectangular bands, according to the band model in the field of thermal radiation. There are in total NB bands and the subscript k stands for the k region of the band model. Both of the two side surfaces S_1 and S_2 of the composite plate are semitransparent, and so are the interfaces P and Q. The reflection of the interfaces is diffuse.

NUMERICAL METHOD AND EQUATIONS

Energy Equation and the Harmonic Average Thermal Conduction Coefficient

For the b layer of a participating media, the energy equation of one-dimensional transient coupled radiation and conduction heat transfer for the i control volume can be expressed as:

$$\rho_b c_b \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_b \frac{\partial T}{\partial x}\right) - \frac{\partial q^r}{\partial x} \quad (1)$$

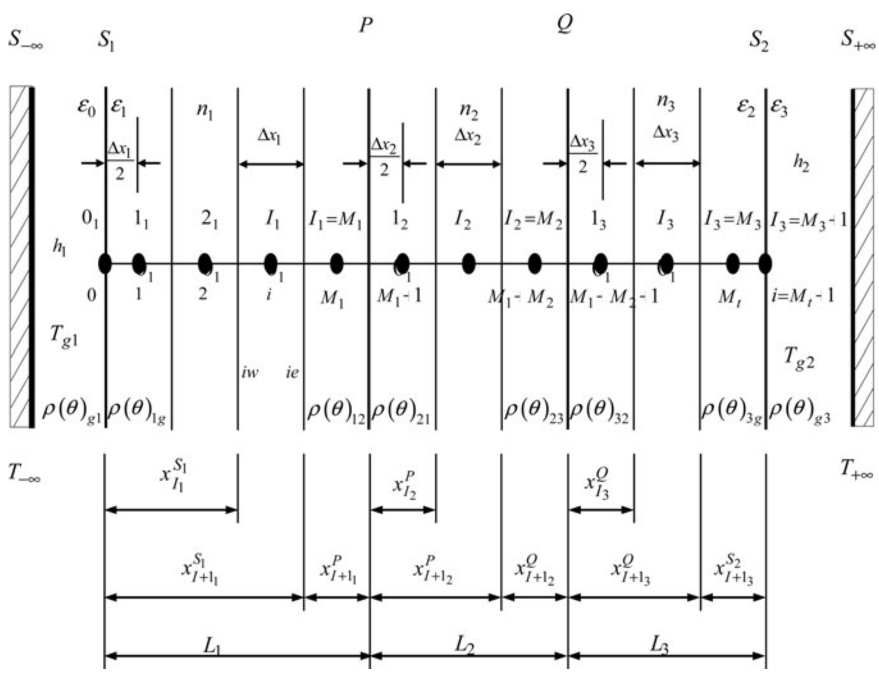

Figure 2 Physical model of transient state coupled radiation and conduction heat transfer in a three-layer semitransparent composite plate.

Then Eq. (1) can be discretized by a fully implicit scheme into the following:

$$\rho_b c_b \Delta x_b \frac{T_i^{m+1} - T_i^m}{\Delta t} = \frac{k_{ie}\left(T_{i+1}^{m+1} - T_i^{m+1}\right)}{(\delta x)_{ie}} - \frac{k_{iw}\left(T_i^{m+1} - T_{i-1}^{m+1}\right)}{(\delta x)_{iw}} + \Phi_i^{r,m+1} \quad (2)$$

where k_{ie} and k_{iw} separately stand for the harmonic average thermal conduction coefficient of the interface ie and iw, and $(\delta x)_{ie}$ and $(\delta x)_{iw}$ separately stand for distance between the node i and $i+1$, i and $i-1$:

$$(\delta x)_{ie} = (\Delta x_i + \Delta x_{i+1})/2 \quad (3)$$

$$k_{ie} = \frac{\Delta x_i + \Delta x_{i+1}}{\Delta x_i / k_i + \Delta x_{i+1} / k_{i+1}} \quad (4)$$

$$(\delta x)_{iw} = (\Delta x_i + \Delta x_{i-1})/2 \quad (5)$$

$$k_{iw} = \frac{\Delta x_{i-1} + \Delta x_i}{\Delta x_{i-1}/k_{i-1} + \Delta x_i / k_i} \quad (6)$$

in which Δx_i and k_i are separately the thickness and thermal conduction coefficient of the i control body, and when $M_1 + \cdots + M_{b-1} < i \le M_1 + \cdots + M_b$, that is, the node i belongs to the b layer of media, $\Delta x_i = \Delta x_b$ and $k_i = k_b$.

Consider that Eqs. (3), (4), (5), and (6) have actual meanings for the control body at the interface.

When $i = M_1 + \cdots + M_{b-1} + 1$, Eqs. (3), (4), (5), and (6) can be expressed as:

$$(\delta x)_{iw} = \frac{(\Delta x_b + \Delta x_{b-1})}{2} \quad (7)$$

$$k_{iw} = \frac{\Delta x_{b-1} + \Delta x_b}{\Delta x_{b-1}/k_{b-1} + \Delta x_b/k_b} \quad (8)$$

$$(\delta x)_{ie} = \Delta x_b \quad (9)$$

$$k_{ie} = k_b \quad (10)$$

When $i = M_1 + \cdots + M_b$, we have:

$$(\delta x)_{ie} = \frac{(\Delta x_b + \Delta x_{b+1})}{2} \quad (11)$$

$$k_{ie} = \frac{\Delta x_{b+1} + \Delta x_b}{\Delta x_{b+1}/k_{b+1} + \Delta x_b/k_b} \quad (12)$$

$$(\delta x)_{iw} = \Delta x_b \quad (13)$$

$$k_{iw} = k_b \quad (14)$$

When $M_1 + \cdots + M_{b-1} + 1 < i < M_1 + \cdots + M_b$, we have:

$$k_{iw} = k_{ie} = k_b \quad (15)$$

$$(\delta x)_{iw} = (\delta x)_{ie} = \Delta x_b \quad (16)$$

The Radiation Source Term and the Boundary Condition

In Eq. (2) Φ_i^r is the radiation source term of the i control body, which is the increase of the internal energy produced from the radiation, $\Phi_i^r = q_{iw}^r - q_{ie}^r$, with: q_{iw}^r the radiation heat flow through the left interface of the i control body and q_{ie}^r the radiation heat flow through the right interface of the i control body.

Define $q_{1\to S_1}^{cd}$ as the heat the node 1 conducts to the surface S_1; $q_{S_1\to g1}^{cv}$ is the convective heat between the surface S_1 and the surrounding fluid; $q_{M_t\to S_2}^{cd}$ is the heat the node M_t conducts to the surface S_2; and $q_{S_2\to g2}^{cv}$ is the convective heat between the surface S_2 and the surrounding fluid. Then for the surface S_1, $q_{1\to S_1}^{cd} = q_{S_1\to g1}^{cv}$, the discrete format of which is

$$2k_1\left(T_1 - T_{S_1}\right) / \Delta x_1 = h_1\left(T_{S_1} - T_{g1}\right) \quad (17)$$

and for the surface S_2, $q_{M_t\to S_2}^{cd} = q_{S_2\to g2}^{cv}$, and the discrete format is

$$2k_3\left(T_{M_t} - T_{S_2}\right) / \Delta x_3 = h_2\left(T_{S_2} - T_{g2}\right) \quad (18)$$

Further, the linearity coefficient of the radiation source term can be expressed as the following:

$$Sc_i^{n+1} = \sigma \sum_{k=1}^{NB} \Bigg\{ 3n'_{i,k} 2 \Bigg(\sum_{j=1}^{M_t} [V_i V_j]_{k,t-t} + [V_i S_{-\infty}]_{k,t-t} + [V_i S_{+\infty}]_{k,t-t} \Bigg) A_{k,T_i}\left(T_i^n\right)^4 \sum_{j=1}^{M_t} n'_{j,k} 2 [V_j V_i]_{k,t-t} \times A_{k,T_j}\left(T_j^n\right)^4 + [S_{+\infty} V_i]_{k,t-t} A_{k,T_{+\infty}} T_{+\infty}^4 + [S_{-\infty} V_i]_{k,t-t} A_{k,T_{-\infty}} T_{-\infty}^4 \Bigg\} \quad (19)$$

$$Sp_i^{n+1} = \sigma \sum_{k=1}^{NB} 4n'_{i,k} 2 \Bigg\{ \sum_{j=1}^{M_t} [V_i V_j]_{k,t-t} + [V_i S_{-\infty}]_{k,t-t} + [V_i S_{+\infty}]_{k,t-t} \Bigg\} A_{k,T_i}\left(T_i^n\right)^3 \quad (20)$$

Table 1 Preliminary parameters of numerical simulation

Structure	SiC layer	PCs layer	Substrate layer
Thickness (μm)	1	2	200
Thermal conductivity (W/(m-K))	56	2.1	18.4
Specific heat (J/(kg-K))	344	627	637
Density (g/cm^3)	3.2	5.85	8.05
Refractive index	2.65	2.35	2.19
Emissivity	0.8	0.7	0.5

RESULTS AND DISCUSSIONS

Preliminary Parameters and Simulation Conditions

Table 1 shows the parameters provided in the experiment, which are used as preliminary parameters for simulation.

Simulation conditions are listed as the following. The structure is simplified to a one-dimensional model with three layers, and the grid number is specified as 40. The heat flux of the outside boundary condition is set as 100 kW/m^2, and the initial temperature is set as 300 K. In addition, the temperature of the outside surrounding is 5 K, with natural convection inside the system.

Heat Transfer Characteristics

The time-varying temperature distribution of the internal and the external surface can be acquired by numerical calculation. However, the temperature difference between the internal and external surfaces is too small to discriminate. By comparing nondimensional temperatures difference of the internal and the external surfaces, Figures 3 and 4 show the varying characteristics with/without photonic crystals, respectively.

From Figures 3 and 4, it is discovered that when there is no PCs coating, the temperatures difference between the internal and the external surfaces of the substrate has a tendency of eventual increase, while it has a tendency of gradual decrease when there is a PCs coating.

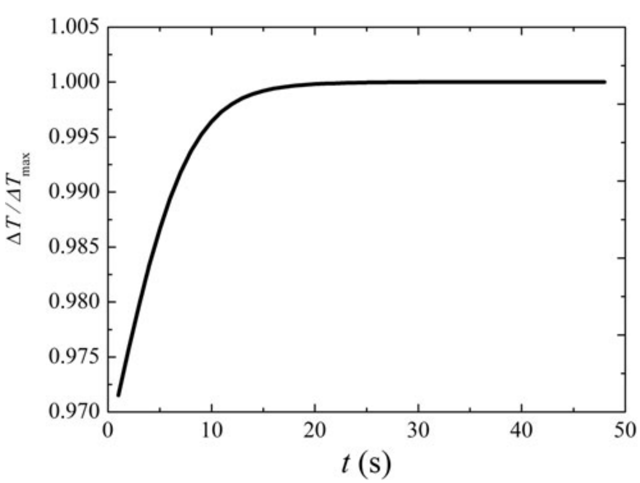

Figure 3 The nondimensional temperature difference of the internal and the external surfaces varying with the time (without PCs).

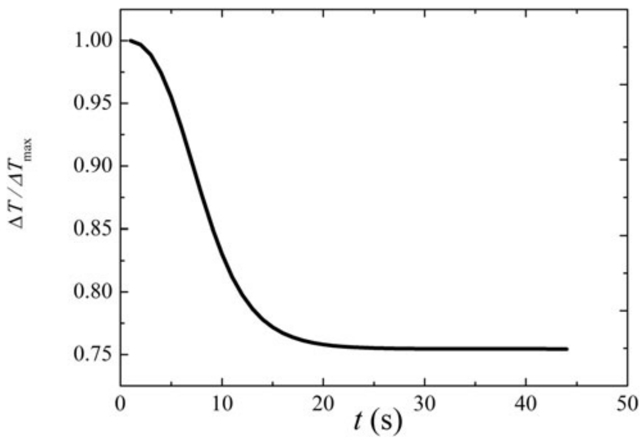

Figure 4 The nondimensional temperature difference of the internal and the external surfaces varying with the time (with PCs).

Specify the coordinate of the external surface as $x = 0$ and the internal surface as $x = 1$, and Figures 5, 6 7, and 8 show the transient temperature distribution inside the structure at different times when there are photonic crystals and when there are not. The results indicate that the temperature gradient inside the PCs layer is relatively larger.

By further calculation, the distribution of nondimensional heat flux at different times, with PCs and without, can be acquired, and is shown in Figures 9 and 10.

In Figure 9, it is estimated that heat flux becomes steady at about 40 kW/m^2 with time varying, while in Figure 10, it is at about 50 kW/m^2. It is also found from the contrast between the two situations that the heat flux has a decrease of about 12 kW/m^2 when there is photonic crystals coating, which is about 10%, and the temperature has decreased about 70 K. Therefore, the thermal protection structure proposed in the current study is shown to be effective.

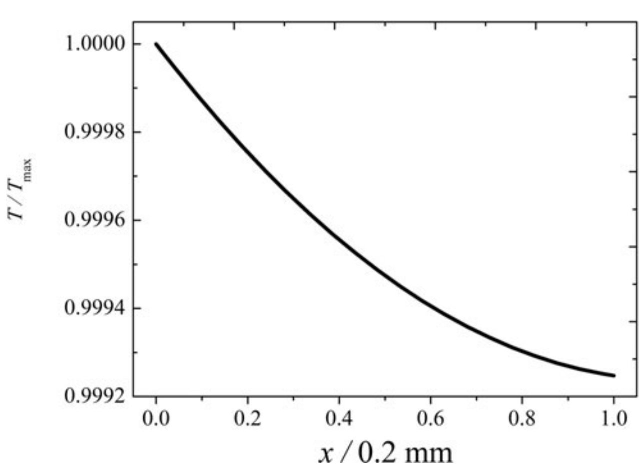

Figure 5 The nondimensional temperature profile when $t = 5$ s (without PCs).

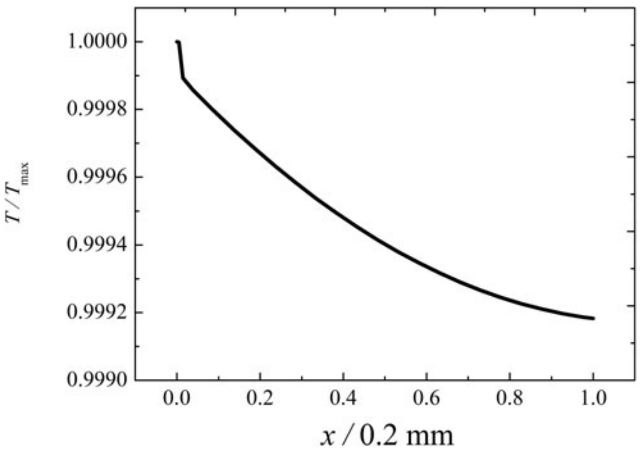

Figure 6 The nondimensional temperature profile when $t = 5$ s (with PCs).

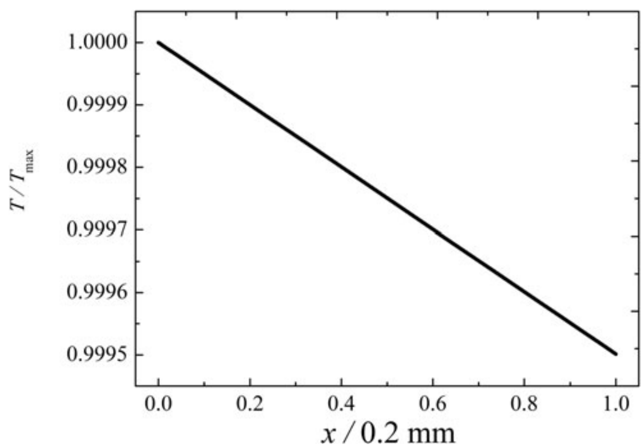

Figure 7 The nondimensional temperature profile when $t = 45$ s (without PCs).

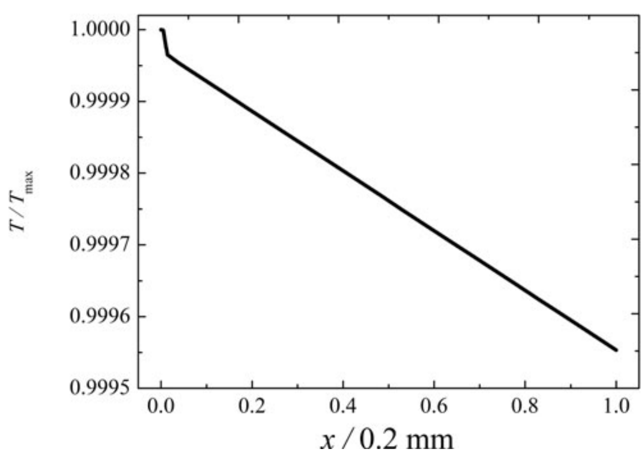

Figure 8 The nondimensional temperature profile when $t = 45$ s (with PCs).

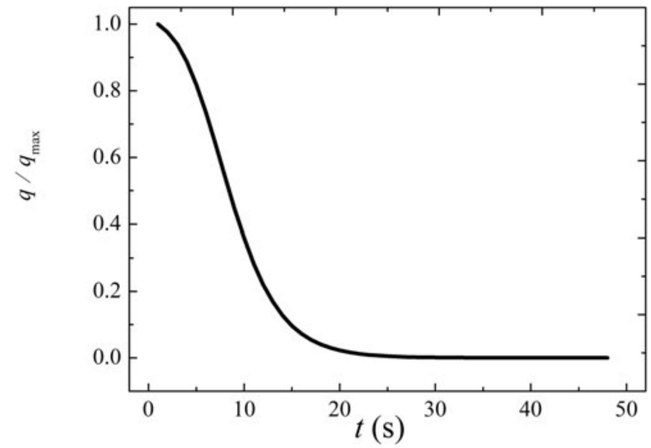

Figure 9 The nondimensional difference of heat flux between the external and the internal surfaces varying with the time (without PCs).

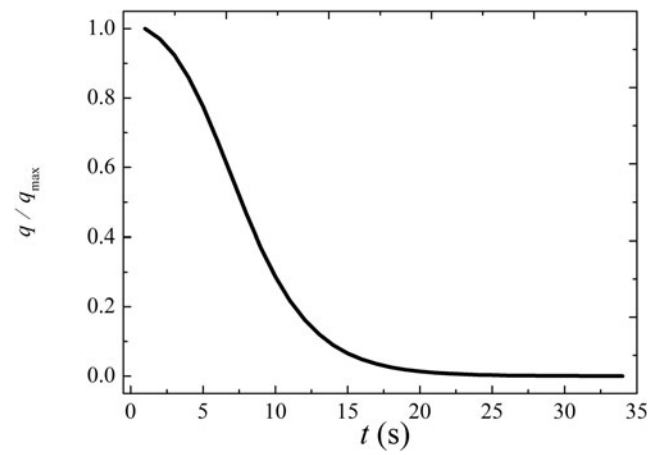

Figure 10 The nondimensional difference of heat flux between the external and the internal surfaces varying with the time (with PCs).

CONCLUSIONS

In this paper, heat transfer characteristics of an innovative thermal protection system based on three-dimensional photonic crystals (SiC-3D PCs) are discussed. Based on the actual structure with coating material containing photonic crystals, a macroscopic model of one-dimensional coupled conduction–radiation heat transfer among three layers composed by semitransparent media is established. Further, according to preliminary physical parameters, back response temperature of the substrate to the heating from external flow field under two conditions is discussed, namely, with photonic crystals coating and without photonic crystals coating in the structure. When there is no PCs coating, the subtraction of the temperatures of the internal and external surfaces of the substrate has a trend of gradual increase, while the subtraction has a trend of gradual decrease when there is PCs coating. The transient temperature distribution inside the coating indicates that the temperature gradient inside the PCs layer is relatively larger. The distribution of the heat flux at different times when there are photonic crystals or not indicates that the heat flux has a decrease of about 12 kW/m^2 when there are photonic crystals, which is about 10%, and the temperature has a decrease of about 70 K. In addition, the comprehensive thermal protection characteristic of the current structure has been analyzed, with considerations of factors as reflection, radiation, and heat transfer process. Therefore, the effect of the thermal protection structure proposed in the current study is shown to be effective.

NOMENCLATURE

c	thermal capacity (J/(kg-K))
k	thermal conduction coefficient (W/(m^2-K))
M	symbol for knot in the layer (—)
n	refractive index (—)
h	heat transfer coefficient (W/(m^2-K))
L	length of the space (m)
q^r	radiation source term (J)
R, r	dimension of the gas or air passages (mm)
Sc, Sp	linearity coefficient of the radiation source term
S_1, S_2	surfaces of the composite plate (—)
T	temperature (K)
t	time (s)
$V_i V_j$	transfer coefficients between volumes (—)
x	position

Greek Symbols

α	absorption coefficient (—)
γ	transmittance (—)
κ	selective media absorption coefficient (—)
ρ	reflectivity (—), density (kg-m^{-3})
σ	scattering coefficient (—)

Subscripts

b	layer of participating media
k	region of the band model
i	internal knot
ie	distance between the node

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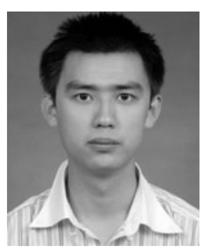

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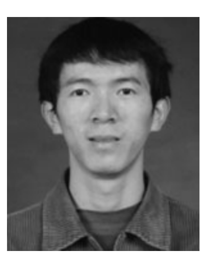

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