Investigation of thermoelectric SiC ceramics for energy harvesting applications on supersonic vehicles leading-edges

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Abstract. Utilizing thermoelectric technology to aerodynamic heat harvesting on the leading-edge is worth noticing in the thermal protection systems. In this paper, a nose-tip model in a supersonic flow field is developed to predict the thermoelectric performance of SiC ceramics structures. The generation performance is numerically investigated in terms of the computational fluid dynamics and the thermal conduction theory. The output power and energy efficiency of the nose-tip model are obtained with Mach number varying from 2.5–4.5. The generated power reaches 1.708 W/m² at a temperature difference of 757 K at $M = 4.5$. With respect to the Thomson effect, the output power decreases rapidly. However, larger output power and energy efficiency would be obtained with the increase of Mach number, with or without considering the Thomson heat. Moreover, under the higher Mach numbers, larger range of output current value is available.

Keywords. Thermoelectric conversion efficiency; supersonic vehicles; nose-tip model; silicon carbide; Thomson heat.

1. Introduction

There is a severe aero-heating when an aircraft cruises at high velocity in atmosphere. To avoid the damage, the huge aerodynamic heat on the fuselage structures needs to be dispersed by the thermal protection system of vehicles (Nagalingam *et al* 2010; Prabhu Swamy *et al* 2010; Hegde *et al* 2012; Lu and Liu 2012a). In fact, the dispersed aerodynamic heat is a waste of energy. If the excess heat was effectually transformed into electric energy, the operating pressure of the thermal protection system (Lu and Liu 2012b) and the power supply system of the vehicles would be reduced and the payload would be increased. Thermoelectric conversion techniques show a novel solution.

Thermoelectric conversion technology enables the direct conversion between heat and electric energy (Rowe 1995, 2005). Since 1950s, with the development of physical theories, like the semiconductor and quantum theory, the research on thermoelectric materials has thrived and their applications have been expanded. Nowadays, the thermoelectric technology has been applied in microelectronics (Gupta *et al* 2011), new energy (Stokes 2010) and the relevant fields. In aeronautics and astronautics, the thermoelectric conversion techniques have achieved significant advances in radioisotope thermoelectric generators (O'Brien 2008), but their adoption in aerodynamic heat harvesting of high speed vehicles is not widely reported. The severe aero-heating on the surface and the safety requirement of the pilot and apparatus in the cabin

lead to the large temperature difference between the in-wall and the outer surface of vehicles and the temperature difference is the prerequisite of the use of the thermoelectric generation technology. By the use of thermoelectric conversion structures heat will be transformed into electricity.

SiC ceramics and composites are good high-temperature thermoelectric materials and structural materials with low thermal expansion coefficient, radiation resistance, oxidation resistance, etc. They are potential materials for such thermoelectric structures. However, their thermal conductivity is large (Ikuko *et al* 2008; Jang and Sakka 2008), which will reduce the temperature difference between the cold and hot sides of materials resulting in low thermoelectric figure of merits. In order to reduce the effective thermal conductivity, porosity has been greatly increased in the previous studies (Kato and Aruga 1997; Wei and Li 2007). Unlike the dense ones, the porous ceramics show relatively low mechanical properties. It is shown that doping elements with good electric conductivity, such as Au, C (Fujisawa and Hata 2008; Nakatsugawa and Nagasawa 2009) etc, can improve the power factors of SiC ceramics, however, the thermal conductivity would be increased consequently.

This paper purposes an application of silicon carbide as thermoelectric materials for the thermoelectric energy conversion on supersonic vehicles' nose-tips. Much research has been done on the thermoelectric properties of various SiC materials, yet few experimental studies have been published regarding the thermoelectric properties of the polymer-derived consolidated SiC-based ceramics, which are widely applied for aerospace/aircraft structures. For this

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Figure 1. Schematic of nose-tip (length in mm).

Figure 2. Grid of simulation model.

reason, we prepared the dense SiC ceramics samples with polycarbosilane as the pre-ceramic precursor and examined their thermoelectric properties quantitatively. A cone-shaped nose-tip model in a supersonic flow field was developed to predict the thermoelectric energy conversion performance of SiC ceramics structures. The computational fluid dynamics and the thermal conduction theory were employed to calculate the output power and energy efficiency of the nose-tip. The Mach number and Thomson heat as a factor in the thermoelectric performance were discussed.

2. Computation scheme and materials properties

2.1 Numerical method of flow field and nose-tip region

The design of the nose-tip model in a classical cone shape is shown in figure 1. 3-D Navier–Stokes equations with the shear stress transport turbulence model (Wilcox 1993; Bardina *et al* 1997) are used as the governing equations for the flow field. The convective terms are approximated by van-Leer flux splitting method (van Leer 1997) and the viscous terms by the central difference method. A 5-step explicit

Table 1. Boundary conditions.

Free stream Mach number	Free stream static pressure (kPa)	Free stream static temperature (K)	Cold side temperature (K)
2.5, 3, 3.5, 4, 4.5	5.48	217	300

Figure 3. Schematic of thermoelectric conversion circuitry.

Runge–Kutta scheme is used for the time integration. The distributions of temperature inside the nose-tip are obtained by solving the heat conduction equation (Tao 2001) with finite element method. Figure 2 shows grid of the simulation model.

The boundary conditions are shown in table 1. The wall boundary conditions are assumed as no-slip and ignore the heat-transfer by radiation for the volume of the nose-tip. The cold side temperature of the nose-tip is assumed to be 300 K (as the normal atmospheric temperature).

2.2 Calculation of thermoelectric conversion efficiency

Displayed between cold and hot sides, the thermoelectric voltage arises in thermoelectric materials. In this work, only the thermoelectric performance of the nose-tip is considered so as to focus on the recovering capability of thermoelectric nose-tip. As shown in figure 3, the effective circuit of thermoelectric nose-tip model consists of the nose-tip power supply of which the thermoelectric voltage (V) can be expressed as:

$$V = |\alpha_H T_H - \alpha_C T_C|, \quad (1)$$

where α_H , α_C are the Seebeck coefficient (V/K) on hot and cold sides, respectively; T_H and T_C stand for the temperature (K) of hot and cold sides, respectively. The rates of the supply heat flux on hot side (Φ_H) and the removal heat flux on cold side (Φ_C) can be calculated as:

$$\Phi_H = \alpha_H T_H I - Q_{\text{Con-H}} - 0.5 I^2 R, \quad (2)$$

$$\Phi_C = \alpha_C T_C I - Q_{\text{Con-C}} + 0.5 I^2 R, \quad (3)$$

Figure 4. Peltier coefficient and electric resistivity of SiC sample.

where $\alpha_H T_H$ and $\alpha_C T_C$ stand for the Peltier coefficient on hot and cold sides, respectively, $Q_{\text{Con-H}}$ and $Q_{\text{Con-C}}$ are the conductive heat rate through the hot and cold sides, which are equal when thermal conductivity (κ) is constant. R is the inherent electric resistance of the nose-tip (Ω). On the right side of the equal mark of the equations, the items from left to right are in turn representing the contribution of the Peltier heat, the conductive heat and the Joule heat. The average electric resistance ($\bar{R}$) of the given nose-tip with a temperature gradient is:

$$\bar{R}_{(T_C, T_H)} = \int_{T_C}^{T_H} R(T) dt / (T_H - T_C), \quad (4)$$

$$R(T) = \rho(T) \cdot \int_0^L dx / (\pi y^2(x)), \quad (5)$$

where $R(T)$ is the electric resistivity as a function of temperature, L the length of nose-tip, $\rho(t)$ the density as a function of temperature, $y(x)$ the x -dependent function of the nose generatrix.

The total electric resistance of the series connected to the thermoelectric generator (nose-tip) is defined as R_L , thus the output power (P) and thermoelectric conversion efficiency (η) are as follows:

$$P = I^2 R_L = \Phi_H - \Phi_C, \quad (6)$$

$$\eta = P / \Phi_H. \quad (7)$$

Thomson heat relates to the rate of generation of reversible heat with results from the passage of a current along a portion of a single conductor along which there is a temperature difference. Although, the Thomson heat is not of the primary importance in the thermoelectric devices, it should be considered in the detailed calculations (Min *et al* 2004; Huang *et al* 2005). Thomson heat (Q_{Th}) can be illustrated by

$$Q_{\text{Th}} = (d\alpha_H/dT \cdot T_H - d\alpha_C/dT \cdot T_C) I \Delta T. \quad (8)$$

Figure 5. Comparison of CFD Stanton numbers to experimental (Saravanan *et al* 2009).

The output power of the nose-tip considering the Thomson heat (P_{Th}) is

$$P_{\text{Th}} = (\alpha_H T_H - \alpha_C T_C) I - Q_{\text{Th}} - I^2 R. \quad (9)$$

2.3 Thermoelectric properties of SiC ceramics

SiC ceramics samples for the thermoelectric parameter measurements were synthesized by thermolysis of polycarbosilane (National Defense University of Technology, Hunan, PRC) (Cheng *et al* 2006) at a temperature of 1273 K in argon atmosphere. The product was ball milled and consolidated by hot-pressing sintering system (High Multi 5000, Fuji-Denpai, Japan). Archimedes method was performed to measure the density of the sintered specimen with deionized water as the immersion medium. Seebeck coefficient, electric and thermal conductivities were measured by four-probe method (ZEM-3, ULVAC-RIKO, Japan) and laser-flashed method (LFA457, Netzsch, Germany) under vacuum in the temperature range from 300–923 K, respectively.

The density of SiC ceramics samples is 1.72 g/cm³. The thermoelectric properties of SiC ceramic sample required for the numerical analysis are exhibited in figure 4. The solid-square marks (■) bond to the Peltier coefficient (π), the product of Seebeck coefficient (α) and absolute temperature (T). The hollow-circle marks (○) bond to the electric resistivity. In order to simplify the calculation, the average thermal conductivity (κ) (5.73 W/(m·K)) of samples are adopted.

3. Numerical methodology validation

Under the same flow condition, the numerical method of the flow field simulation was validated by the related experiment

Figure 6. CFD results of (a) flow field Mach number, (b) flow field temperature and (c) solid region temperature distributions ($M = 3.5$).

Table 2. Heat flux, temperature difference and electric resistivity under different M conditions.

M	Q/W	$\Delta T/K$	R/Ω
2.5	123	164	2.08
3.0	255	275	1.88
3.5	429	421	1.65
4.0	627	578	1.45
4.5	857	757	1.27

in the open literature (Saravanan *et al* 2009). As shown in figure 5, the predicted Stanton numbers (St) along the surface of the hemisphere-cone nose are compared with the experimental data. Based on the free stream condition, the Stanton number is given by the expression

$$St = \frac{q_w}{(T_{aw} - T_w) \rho_\infty c_{p\infty} u_\infty}, \quad (10)$$

$$T_{aw} = T_\infty \left\{ 1 + \sqrt[3]{Pr} \left[\frac{(\gamma - 1)}{2} \right] Ma_\infty^2 \right\}, \quad (11)$$

where q_w is the heat flux along the nose-tip surface, T_{aw} the temperature of thermal isolation wall, T_w the temperature of the nose-tip surface, ρ_∞ the density of the free stream, $c_{p\infty}$ the constant-pressure specific heat of the free stream, u_∞ the velocity of the free stream, T_∞ the static temperature of free stream, Pr the Prandtl number and γ the specific heat ratio.

The numerical and experimental results are in good agreement with each other. There are eight experimental data points with the simulation accuracies of the remaining points within 15%. The discrepancy is attributed to the computation error, assumption of the simulation model and experimental measurement error.

4. Results and discussion

4.1 Numerical results of flow field and nose-tip region

In the present work, five cases of cruise Mach number are established to investigate the influence of the Mach number

Figure 7. Output power and conversion efficiency vs electric current under different Mach numbers neglecting Thomson effect.

on thermoelectricity conversion capability of the SiC nose-tip (table 1). The distribution of Mach number and temperature in the flow field and the distribution of temperature in the nose-tip region for $M = 3.5$ case are shown in figure 6. With the supersonic flow fluid reaching $M = 3.5$, the aerodynamic heat assembles at the leading side of the nose-tip. The temperature on the hot side is about 721 K, producing a temperature difference of about 421 K. Although SiC ceramics and composites can be used under temperature up to 2000 K (Glass 2008), in this investigation the maximum temperature upon the nose-tip region is about 1000 K ($M = 4.5$).

As shown in table 2, the maximum of temperature difference between the cold and hot sides of the nose-tip (ΔT), the heat flux (Q) along the nose-tip surface and the inherent resistance (R) by are studied numerically. With the Mach number, values of Q and ΔT increase. Inversely the value of R reduces for the reason that the electric resistivity of SiC ceramics decreases with the increase in temperature.

Table 3. Maximum current, maximum output power and maximum efficiency under different M conditions without Thomson effect.

M	$I_{\max}/A$	$P_{\max}/W/m^2$	$\eta_{\max}/\times 10^{-4}\%$
2.5	0.014	0.020	0.820
3.0	0.030	0.080	1.564
3.5	0.057	0.263	3.097
4.0	0.099	0.703	5.612
4.5	0.164	1.708	9.944

Figure 8. Output power and conversion efficiency vs electric current under different Mach numbers considering Thomson effect.

4.2 Thermoelectric conversion performance

Figure 7 shows output power and energy efficiency as a function of current at different Mach numbers. Corresponding to the equations we used, the current dependence of the output power and the energy efficiency are rigid in accordance with parabola curves. The maximum values are achieved at a half of the maximum output current, where R_L equals to R . With the growth of Mach number, the range of the output current, the output power and the energy efficiency increase due to the increase of temperature difference and heat flux resulting from the dramatically enhanced aero-heating. The maximum output current ($I_{\max}$), power ($P_{\max}$) and the energy conversion efficiency ($\eta_{\max}$) of the nose-tip structure under different Mach numbers are listed in table 3.

The energy efficiency of the thermoelectric generation is still very low even at M 4.5. However, it is promised that the thermoelectric energy efficiency will be increased as the Mach number increases. Because with higher Mach number, not only the heat flux and temperature difference but also the thermoelectric properties of SiC ceramics will greatly develop. Both of these two aspects contribute to higher thermoelectric voltage and lower electric resistance, resulting in larger output power and energy efficiency.

Table 4. Maximum current, maximum output power and maximum efficiency under different M conditions with Thomson effect.

M	$I_{Th-\max}/A$	$P_{Th-\max}/W/m^2$	$\eta_{Th-\max}/\times 10^{-4}\%$
2.5	0.012	0.015	0.597
3.0	0.025	0.050	0.985
3.5	0.041	0.130	1.514
4.0	0.063	0.279	2.224
4.5	0.092	0.546	3.171

Figure 9. Ratio of heat flux to total generated power as a function of electric current.

4.3 Effect of Thomson heat on thermoelectric conversion performance

Considering the Thomson effect yield the output power and energy efficiency as a function of the current are shown in figure 8. Thomson heat has a great effect on the output power and the energy efficiency, without changing the tendency of their temperature dependence. The maximum of output current ($I_{Th-\max}$), power ($P_{Th-\max}$) and energy efficiency ($\eta_{Th-\max}$) with respect to the Thomson heat are listed in table 4. Compared to table 3, higher the Mach number, larger the Thomson heat.

To clarify the effect of Thomson heat on the generated thermoelectric power, we introduce the current dependence of Thomson heat to the total generated power ratio in percentage, as figure 9 depicts. With the increase of Mach number, the current dependence of the percentage grows more gradually. That means, at higher Mach numbers, although the Thomson heat is very large, its effect on output power is relatively stable when the current increases. To be specific, the thermoelectric nose-tip should work with lower output electric current under a smaller Mach number condition, in order to reduce the effect of Thomson heat. On the contrary, larger output electric current is encouraged at higher Mach numbers.

5. Conclusions

The thermoelectric dense SiC ceramic materials can be utilized for aerodynamic heat recovery through the temperature difference on supersonic vehicles structures. With the elevated Mach number, the output power and the energy efficiency become much larger. The maximum of the output power reaches 1.708 W/m^2 at $M 4.5$. Overall, the energy efficiency is low, but would be increased by the improvement of the thermoelectric properties of SiC materials. Although the Thomson heat grows larger as Mach number increases, it can be controlled by adjusting the electric current in circuits. Since the Thomson effect would be more stable at that circumstance, larger electric current is encouraged at higher Mach number. Results indicate better thermoelectric performance especially at higher Mach numbers and may supply the fundamental data for the aerodynamic heat limitation by thermoelectric energy conversion in high-speed space transportation systems.

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