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A novel TE-material based thermal protection structure and its performance evaluation for hypersonic flight vehicles

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ABSTRACT

The traditional thermal protection system (TPS) of hypersonic flight vehicles is usually designed for thermal protection purpose only with low efficiency. In this paper, a thermoelectric material based multifunctional TPS structure concept is proposed and the evaluation approach of its mechanical-thermoelectric performance is developed based on a specific vehicle and a typical trajectory. The thermoelectric module in the structure can convert a certain amount of aerodynamic heat into electricity supply. The module consists of *n*-type $Sr_{0.9}La_{0.1}TiO_3$ compound which is fabricated based on the solid state reaction method, and the widely used *p*-type $Ca_3Co_4O_9$. For a specific hypersonic flight vehicle with a typical trajectory curve, the aerodynamic heat is calculated by an engineering-based algorithm, the unsteady mechanical-thermoelectric characteristics of the structure is then analyzed based on a unit cell model and the thermoelectric conversion efficiency is finally evaluated. The results indicate that the multifunctional TPS structure has significant application potentials on the hypersonic flight vehicles.

1. Introduction

For a flight vehicle, the increasing flying speed brings about a large amount of aerodynamic heat and leads to a very harsh thermal environment. For a supersonic vehicle, at some specific locations of leading edge, the temperature may reach to a value of higher than 1800 K [1–3]. Thus, a reliable and efficient thermal protection system (TPS) is essential to ensure the safety of the vehicle.

The first input condition of design and evaluation of a TPS is the aerodynamic heat. There are two main methods to predict the aerodynamic heat, the engineering-based method and the numerical method. During the last decades, numerous relevant studies have been carried on to develop appropriate numerical method (mainly CFD) for the aerodynamic heat prediction of flow fields/vehicle with different configurations [4–8]. For instance, in Ref. [4], the capacity of DNS (direct numerical simulations), LES (large eddy simulations) and RANS (Reynolds-averaged Navier–Stokes) for the prediction of turbulent shock wave were evaluated based on cases of 2D compression and expansion-compression corners, 2D shock impingement, 3D single and double fins. At present, the numerical method still has some challenges, such as the high requirement to mesh generation, especially the grid near the vehicle surface should be very carefully considered since the temperature gradient is very sensitive to the grids resolution. Also, the numerical simulation is a very resource-consuming method and has low efficiency. On the other hand, the engineering-based algorithms and programs, such as MINIVER [9] and LATCH [10] which are developed based on empirical correlations and engineering purposes are very popular. Such methods always contain a series of theories to adapt different flow conditions (e.g., subsonic or supersonic, laminar or turbulent). Thus, they have lower accuracy in comparison with numerical methods. However, they are much more efficient. In this work, a quick TPS evaluation approach is more concerned, and thus an engineering-based method is used to calculate the aerodynamic heat.

A TPS always consists of a high-temperature layer and a below insulation layer. The high-temperature layer is the first layer to withstand the aerodynamic heating, and the candidate materials include C/SiC, C/C, ultra high temperature ceramic, etc. For the insulation layer, the basic requirement should be the low weight and low thermal conductivity [11,12]. Ma et al. [11] developed an integrated TPS with additional insulation layer, and different insulation material/structure including Mullite blanket, ceramic tile and aerogel are evaluated. In fact, the choosing of a TPS material is closely related to the material's own characteristics and the TPS requirement. For instance, the TPS optional materials can be classified into

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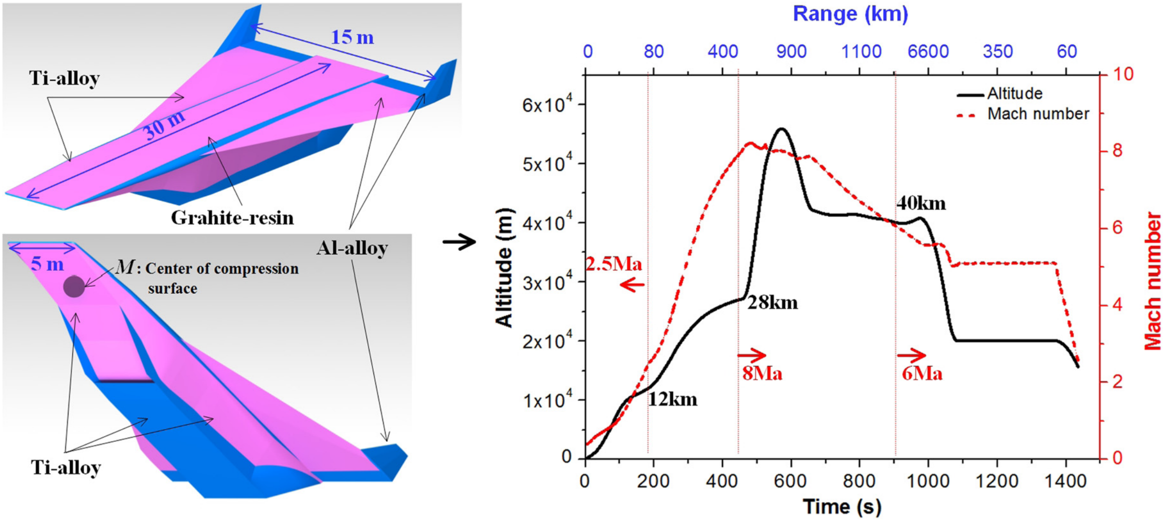

Fig. 1. The vehicle and the trajectory.

two types in general, the ablative and non-ablative materials. For a structure with ablative materials [11,13–16], part of the aerodynamic heat will be taken away by its ablation process, and thus has higher efficiency. However, it is not applicable to a reusable vehicle due to its changing configuration during the flight mission. On the other hand, for a TPS based on non-ablative material [17–19], the surface radiation is the only dissipation of aerodynamic heat, and thus leaves some rooms for the improvement of its efficiency. In this work, a high-efficiency multi-functional TPS structure based on thermoelectric (TE) material is developed.

The TE material and corresponding modules can convert aerodynamic heat into electric energy directly as the well-known Seebeck effect, and the conversion efficiency can reach a value of 5∼20% or even higher with some appropriate treatments like doping and nano-structuring [20]. According to its suitable temperature, the TE material can be classified as room-temperature (e.g., Bi_2Te_3), mid-temperature (e.g., PbTe) and high-temperature ones (Oxide ones). A TE module is always a couple of n- and p-type materials and can be used as an electricity generator under a certain temperature difference. The performance of a TE generator is partly dependent on the temperature difference across the TE material which is related to the performance of additional heat exchangers, Lv et al. [21] studied three typical heat exchangers (air cooling, fluid cooling and heat pipe) and evaluated their influence on TE performance. Lan et al. [22] developed a dynamic model of TE generator for the waste heat recovery of automotive vehicles. For the application of flight vehicles, to the authors' knowledge, the relevant researches are limited: Li and Wang [23] developed an integrated TE module with regenerative cooling system, and analyzed its performance based on the exergy analysis theory; Cheng et al. [24] developed a multi-stage TE module considering the suitable temperature of TE material, and analyzed its thermal protection performance. The very limited research activities motivate further studies.

In this work, a TE material based multi-functional TPS structure is developed. For the p-type material, the widely used high-temperature material $Ca_3Co_4O_9$ [25–27] is adopted, and for the n-type material, a Ti-doped ceramic $Sr_{0.9}La_{0.1}TiO_3$ is fabricated by solid state reaction method. The evaluation approach of its mechanical-thermoelectric performance is developed based on a specific vehicle and a typical trajectory.

2. The vehicle, trajectory and aerodynamic heat

It should be pointed out that under a limiting or an ideal condition, engineering structures can always have good performance, whereas relevant results have certain limitations. Therefore, the evaluation of an engineering system has to be accomplished according to a specific vehicle with specific mission trajectory. For the novel TPS structure proposed in this work, a complete evaluation process including the calculation of input thermal conditions, the mechanical-thermoelectric analysis and the TE conversion calculation is displayed in detail. Such approach can be referenced and used for other similar vehicles and trajectories.

2.1. The vehicle and trajectory

The vehicle and the trajectory studied in this work should be introduced first. Fig. 1 shows the vehicle and the trajectory. The left part is the model of a hypersonic reusable launch vehicle designed by the authors. The black circle on the compression surface is a specific point M that will be considered in the calculation of this work. The size of the vehicle and the general distribution of structure materials are shown in Fig. 1. The vehicle has a length of 30 m, a wingspan of 15 m, and the width of the fuselage is 5 m. The compression surface has an area of about 30 m^2. The structure of the vehicle is divided into several zones of different materials mainly consists of Ti-alloy, Al-alloy and resin based composites, and more detailed descriptions can be found for a similar vehicle in the authors' previous work [28].

The right part of Fig. 1 is its typical trajectory curve in a two-dimensional pattern. The vertical axis is the altitude, the bottom horizontal axis is the flight time while the top one is the flight range. It should be noted that the flight range is not in a linear scale, and the largest value is about 6600 km and then the vehicle will return to the launch field. One can notice that the vehicle will reach 28 km height and its speed will increase from 0 to 8 Ma within 450 s, then it will fly to its highest altitude of about 50 km and accomplish its mission and return. The large amount of aerodynamic heat generated during the trans-atmospheric phase of its launch and re-entry gives rise of great challenges of TPS. In this work, the aerodynamic heat under the trajectory curve shown in Fig. 1 is calculated. The heat is then applied to analyze the thermal protection efficiency of the TPS structure proposed in this work.