Heat-balance Thermal Protection with High Thermal Conductivity Materials for Hypersonic Vehicle

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ABSTRACT

Heat-balance thermal protection is non-ablating thermal protection for leading edge of hypersonic vehicle. Heat will be quickly transferred from high aerodynamic heating area to low aerodynamic heating area, where the energy will be released by radiation. The temperature of high aerodynamic heating area could be reduced to protect the designed structure from being burned down. Heat-balance thermal protection is summarized. The research on high thermal conductivity material for heat-balance thermal protection is introduced.

INTRODUCTION

There is serious aerodynamic heating during hypersonic flight. The heat flux on leading nose whose radius is 20mm can reach 2~3MW/m$^2$ and the wall temperature can reach 1400K when the vehicle Mach number is 7 and flight altitude is 24km. When traditional ablating thermal protection is used, the ablating material is burned out. During the ablation, aerodynamic heating is absorbed and released. However, the designed aerodynamic structure may be burned down, especially the sharp leading edge. The vehicle will be unable to fly in high Mach number if its structure is seriously ablated.

Heat-balance thermal protection is different from traditional thermal protection. Heat will be quickly transferred from high aerodynamic heating area to low aerodynamic heating area, where the energy will be released by radiation. The temperature of high aerodynamic heating area could be reduced to protect the designed structure from being burned down. It is non-ablating thermal protection.

DIFFERENT HEAT-BALANCE THERMAL PROTECTIONS

According to thermal protection mechanism, heat-balance thermal protection can be divided into single heat-balance thermal protection and combinational heat-balance thermal protection. In practice, single heat-balance thermal protection
is hardly used. There are usually more two methods used together to achieve better thermal protect effect, which is shown in Table 1.

As widely used methods, the research on high thermal conductivity material for heat-balance thermal protection is introduced.

| Type              | Thermal Protect Way | Materials                      | Thermal Protect Mechanism                                                                 |
|-------------------|---------------------|--------------------------------|------------------------------------------------------------------------------------------|
| Single            | Using high thermal  | Metal, high thermal conductivity | Heat is conducted quickly with high thermal conductivity.                                  |
|                   | conductivity        | carbon material                |                                                                                           |
|                   | Using fluid         | Air, water, liquid Na, liquid Li | Heat is conducted with fluid flowing                                                       |
| Combinational     | Nano-fluid          | Nano-sized particles with fluid | Heat is better conducted with fluid flowing and high thermal conductivity of Nano-sized particles. |
|                   | Phase-changeable    | Matrix is made of high thermal conductivity material filled with phase-changeable material. | Phase-changeable material will absorb heat while phase is changing. After phase change, material becomes fluid. Matrix made of high thermal conductivity for heat transfer will also keep phase-changeable material from leaking out. |
|                   | Heat-pipe           | Container is made of high heat capacity material and filled with full wetting working fluid. | Working fluid evaporates in evaporator first. Vapor will be transported to condenser, where vapor condenses. Then condensate will return to evaporator through a Wick of suitable capillary structure. |
|                   | Embedded heat-pipe  | Heat-pipe is embedded with high thermal conductivity material | Heat-pipe and high thermal conductivity material can both transfer heat isothermally. And embedded structure is more stable. |

**HEAT-BALANCE THERMAL PROTECTIONS WITH HIGH THERMAL CONDUCTIVITY MATERIAL**

Heat-balance thermal protection with high thermal conductivity material is using high thermal conductivity to transfer heat isothermally. Available materials are high thermal conductivity carbon material and metals such as copper and aluminum. Because metals are usually heavy, they are not first choice to make hypersonic vehicle. If they are processed into foam material to reduce their density, their thermal conductivity will be reduced at the same time [1]. Heat can be transferred quickly in high thermal conductivity carbon material, which is light and stable in extremely hot condition. These properties make high thermal conductivity
carbon material very important in future thermal protection system for hypersonic vehicle.

Until now, there are several carbon materials with high thermal conductivity, including mesophase pitch-based carbon material such as mesophase pitch-based carbon foam, carbon fiber, carbon belt, C/C composites and so on, and pyrolytic Carbon such as high ordered pyrolytic graphite (HOPG), vapor grown carbon fiber (VGCF), carbon nanotube (CNT) and so on. There are data from experiments in Ref. [1] about highest thermal conductivity of various carbon materials. Data are improved and revised and shown in Table 2.

| TABLE 2. HIGHEST THERMAL CONDUCTIVITY OF VARIOUS CARBON MATERIALS AT ROOM TEMPERATURE (W/MK). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| K-1100 carbon foam  | mesophase C/C  | HOPG            | VGCF            | Individual single-wall CNT | Single-wall CNT | Multi-wall CNT | Single-Layer graphene |
| CF11             | CFII            | [4]             | [5]             | [6]             | CNT [8]         | CNT [9]         | [10]            |
| 1170             | >1500           | 746             | 1600-2000       | 1950            | ~3500           | 1750-5800       | >3000           | ~4840-5300       |

Besides experiments, theory analyses also validate high thermal conductivity of carbon Nanotube. Combining equilibrium and nonequilibrium molecular dynamics simulations with accurate carbon potentials, Berber [11] determined the thermal conductivity of carbon nanotubes, which is an unusually high value, 6600 W/mK at room temperature. The thermal conductivity of several single-wall carbon nanotubes has been calculated by Osman [12] over a temperature range of 100–500 K using molecular dynamics simulations with the Tersoff–Brenner potential for C–C interactions. And the result is about 1500~3000 W/mK.

In order to research on thermal conductivity in heat-balance thermal protection, Jiang [13] proposed two expression parameters for heat transfer in solid medium. High thermal conductivity C/C and low thermal conductivity C/C were studied together to compare with each other. And the effect of thermal conductivity of different materials on heat-balance thermal protection was analyzed. Jiang [14] also did experimental research on stagnation point temperature for heated sphere-cylinder models with and without the high conducting graphite heat-balance thermal protection technology. Their results are shown in Table 3 and Fig. 1.

| TABLE 3. COMPARISON OF STAGNATION POINT TEMPERATURE FOR HEATED SPHERE-CYLINDER MODELS WITH AND WITHOUT THE HIGH CONDUCTING GRAPHITE HEAT-BALANCE THERMAL PROTECTION TECHNOLOGY. |
|-----------------|-----------------|-----------------|-----------------|
| Models          | Calculation results/K | Experiment results/K |
| C/C model       | 2199             | 2170             |
| Heat-balance model | 1890            | 1870             |
| Percentage for temperature reduction (\% )          | 16.3               | 16.0              |
a Antioxygenic C/C model  
b Antioxygenic C/C + high conducting graphite model

**Figure 1.** Test result comparison of antioxygenic C/C model and antioxygenic C/C + high conducting graphite model in a wind tunnel.

Sun [15-18] did research on thermal protection effect of embedded high thermal conductivity materials by numerical and experimental research. The structure of heat-balance thermal protection is used to prevent the sharp leading edge of hypersonic vehicle from serious aerodynamic heating [15]. The effect of thickness and black level of heat-resistant materials and thermal conductivity of high thermal conductivity material on wall temperature are discussed. The maximum temperature of the head decrease by 13.6% and the minimum temperature of after-body increase by 16.7% when Mach number is 6.5. The effect of high thermal conductivity materials for hypersonic vehicle nosetip structure was validated [16]. The influences of structure parameter and material attributes of coating and thermal conductivity of high conductivity carbon materials on thermal protection were discussed. The maximal temperature of the nosetip which used heat-balance thermal protection structure was reduced by 21.9% and the lowest temperature of after-body was increased by 15.2% when Mach number is 9. With heat-balance thermal protection, the transfer of heat from head to after-body is achieved, the thermal load of the front head is weakened and the ability of leading-edge thermal protection is strengthened.

The structure of embedded high thermal conductivity layer heat-balance thermal protection is considered as thermal protection system [17]. The influences of aerodynamic heat flux ratio and the area ratio of radiative surfaces were discussed. The maximum outer surface temperature and the inner surface temperature were reduced by 9.1% and by 31.5% respectively. Both high temperature region and low temperature region were blocked in the external layer and the inner temperature distributions were nearly isothermal.

Sun [18] also did experiment on steel heat-balance leading edge structure embedded copper which is high thermal conductivity materials. The steel leading edges with and without copper embedded (see Fig. 2) were heated with the same spherical short arc xenon lamp which was replaced aerodynamic heating with. The temperatures of head and tail of different models were compared (see Fig. 3) to validate thermal protection effect of the heat-balance leading edge structure.

![Figure 2. Experimental models.](image-url)
Liu [19] proposed a numerical model of a heat-balance thermal protection structure with high thermal conductivity C/C material embedded for reusable launch vehicle. Thermal protection effect on the structure was studied with experiment and numerical simulation, whose results showed good agreement with each other. With heat-balance thermal protection structure, the temperature on stagnation point decreased from 2345K to 1980K and the temperature on tail part increased from 867K to 982K (see Fig. 4). The results showed that heat-balance thermal protection could reduce the temperature on stagnation point efficiently and made the whole structure isothermal, which greatly reduced heat stress caused by temperature difference. Critical parameters for heat-balance thermal protection were analyzed. The results showed that it was an effective method to decrease the stagnation temperature by reducing the thickness of the heat-resisting material, but the resulting strength problem should also be taken into account. Interface contact thermal resistance had a significant influence on the thermal protection effect, and in order to achieve effective thermal protection, the interface contact thermal resistance should be lowered to about $1\times10^{-5}$ K·m$^2$·W$^{-1}$ through fabrication processing.

These research works by theory analysis, experiments and numerical simulation validated the feasibility and effect of heat-balance thermal protection by using high thermal conductivity materials. With these works, heat-balance thermal protection could be known qualitatively and quantitatively.

**WORKING CONDITION OF HEAT-BALANCE THERMAL PROTECTIONS**

During hypersonic flight, there is serious aerodynamic heating, especially on leading edge. The heat flux on leading nose whose radius is 20mm can reach 2~3MW/m$^2$ and the wall temperature can reach 1400K when the vehicle Mach number is 7 and flight altitude is 24km. And the heat flux on leading nose whose radius is 1~2mm can reach 4~5MW/m$^2$ and the wall temperature can reach
1600~1900K when the vehicle Mach number is 6 and flight altitude is 25km. When
the vehicle Mach number is 10~20 and flight altitude is about 100km and the heat
flux on leading nose whose radius is 10~30mm can reach 10MW/m² and the wall
temperature can reach 2000K.

When wall temperature is larger than critical temperature such as melting point,
ultimate strength, and the aerodynamic structure has to be kept from burning down,
heat-balance thermal protection could be a good choice for thermal protection
system. However, the working temperature for high thermal conductivity materials
should be lower than their melting points.

With the use of heat-balance thermal protection with high thermal conductivity
materials for hypersonic vehicle noetip structure [16], the maximal temperature of
the noetip which used heat-balance thermal protection structure was reduced by
21.9% and the lowest temperature of after-body was increased by 15.2% when
Mach number is 9. With heat-balance thermal protection, the transfer of heat from
head to after-body is achieved, the thermal load of the front head is weakened and
the ability of leading-edge thermal protection is strengthened.

CONCLUSIONS

Heat-balance thermal protection is non-ablating thermal protection, which can
prevent the aerodynamic structure of hypersonic vehicle from burning down with
the serious aerodynamic heating. Heat-balance thermal protection provides very
high effectively thermal conductivity which allows heat to be transferred from the
hot leading edge to large cool surfaces for radiation into space. It is validated by
research with theory analysis, numerical simulations and experiments. In China, we
are still at the primary stage. Learning abroad is a good way to make fewer
mistakes while developing quickly. In order to develop heat-balance thermal
protection, we could consider:

1. Develop or choose new materials which is lighter, higher melting point,
   higher thermal capability and higher thermal conductivity;
2. Design new structure for high thermal conductivity materials;
3. Design new heat-balance thermal protection.

Heat-balance thermal protection is a different thought changing from heat proof
into heat control, which keep the whole vehicle as isothermal as possible. The
research on heat-balance thermal protection will offer more efficient practical
solutions to solve the seriously aerodynamic heating on hypersonic vehicle.

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