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Heat-balance Thermal Protection with Heat Pipes 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 heat-pipe for heat-balance thermal protection is introduced.

1 Introduction

There is serious aerodynamic heating during hypersonic flight. The heat flux on leading nose whose radius is 20mm can reach 2~3MW/m2 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 shape 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.

2 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 heat-pipe for heat-balance thermal protection is introduced.

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Table 1. Different heat-balance thermal protections

Type	Thermal Protect Way	Materials	Thermal Protect Mechanism
Single	Using high thermal conductivity material	Metal，high thermal conductivity carbon material	Heat is conducted quickly with high thermal conductivity.
	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 material in special matrix	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.

3 Heat-balance thermal protections with high thermal conductivity material

Heat-pipe mainly uses fluid to transfer heat. Heat pipes transfer heat nearly isothermally by the evaporation and condensation of a working fluid, as illustrated in Fig. 1. The heat is absorbed within the heat pipe by evaporation of the working fluid. The evaporation results in a slight internal pressure differential that causes the vapor to flow from the evaporator region to the condenser region, where it condenses and gives up heat. The cycle is completed with the return flow of the liquid condensate to the evaporator region by the capillary action of a wick. When heat-pipe is used to cool hypersonic leading edge, it can be design as Fig. 2.

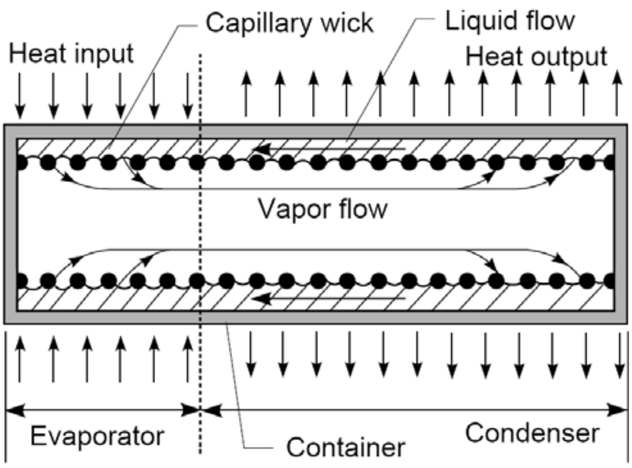

Figure 1. Schematic diagram of the operation of a heat pipe showing the heat-pipe container, working fluid, and wick.

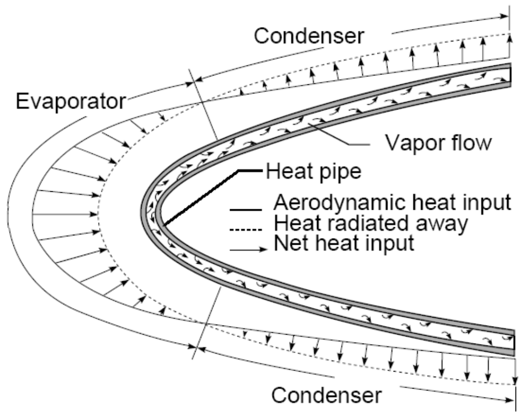

Figure 2. Schematic diagram of a heat-pipe-cooled leading edge showing regions of net heat input (evaporator) and net heat output (condenser)

Working fluid is an important factor in heat-pipe working effect. The choice of working fluid is related with working conditions and will affect heat transfer. There are appropriate working fluids at different temperatures for heat-pipe in Fig. 3 [1]. From Fig. 3, it is known that metals such as K, Na and Cs could be used as working fluid when temperature is high. In the same temperature region, like 550K-740K, Cs is a better choice for working fluid than K. But K will be better when temperature is higher than 740K [2].

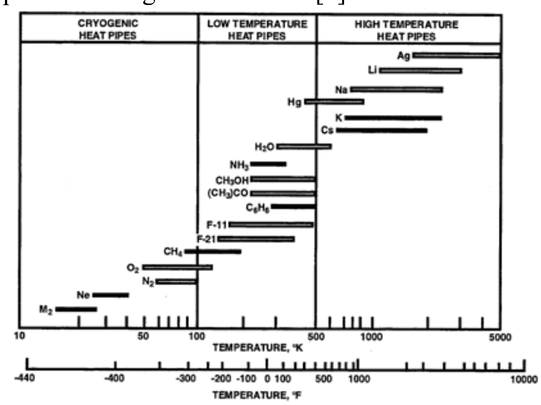

Figure 3. Appropriate working fluids at different temperatures for heat-pipe [1]

Heat-pipe does not need special energy supply to work, and it has high thermal conductivity. The hard container can be used as support structure. These advantages enable heat-pipe to be widely used in heat control and heat-balance thermal protection. In early 1966, a first W-Li super high temperature heat-pipe was developed [3]. In last century 70's, heat-pipe was used for heat control on space vehicles [4-6]. Donovan [7] used heat-pipe as heat-balance thermal protection for missile fin. Buffone [8-9] used liquid metal (Na and Li) heat-pipe to cool rocket nozzle wall.

The research on heat-pipe cooled leading edge for hypersonic vehicle began in last century 70's. NASA Langley Research Center (LaRC), through a contractual study, analytically verified the viability of heat pipes for cooling stagnation regions of hypersonic vehicles [10]. Niblock [11] proposed four space shuttle wing leading edge concepts, in one of which is a liquid-metal/superalloy heat-pipe-cooled concept. The heat-pipe-cooled concept was determined to be a feasible and durable design concept, but was slightly heavier than the other candidate concepts. In 1973, Camarda [12] fabricated a half-scale shuttle-type heat-pipe-cooled leading edge to verify feasibility of the concept (see Fig. 4). This model was tested by a series of radiant heat and aerothermal tests at NASA LaRC from 1977 to 1978 to verify heat-pipe transient, startup, and steady-state performance [12-14]. In 1979, to optimize a heat-pipe-cooled wing leading edge for a single-stage-to-orbit vehicle, Peeples's [15] study indicated that the mass of a shuttle-type heat-pipe-cooled leading edge could be reduced by over 40 % by use of a more efficient structural design. In 1986, Boman [16] designed and fabricated a sodium/superalloy heat-pipe- cooled leading edge component for an advanced shuttle-type vehicle. This advanced shuttle-type heat pipe was 1.83m long and was tested by radiant heating and by induction heating [17-18].

In 1988, a Haynes 25/sodium leading-edge-shaped heat pipe with a "D-shaped" cross section was designed and tested by Clark [19]. The heat pipe had a length of 30cm, and a wall thickness of 0.076cm. Thermal performance, vibration sensitivity, and critical heat flux tests were conducted. Straight niobium/lithium heat pipes with a "D-shaped" cross section and a 0.06cm thick wall have also been fabricated and tested by Wojcik[20-21]. These heat pipes had an oxidation resistance coating on the outer surface.

Figure 4. Heat-pipe cooled leading edge [12]

In 1992, Glass designed a heat-pipe-cooled leading edge which could reduce the leading-edge mass by over 50% compared to an actively cooled leading edge and could completely eliminate the need for active cooling, and has the potential to provide failsafe and redundant features [22]. It was a Mo-Re heat-pipe, used lithium as the working fluid and embedded in C/C (see Fig. 5). From 1992 to 2006, Glass [22-29] did a lot of research on heat-pipe-cooled leading edge by theory analysis, numerical simulation and experiments. During their tests, the heat-pipe-cooled leading edge worked nearly isothermally.

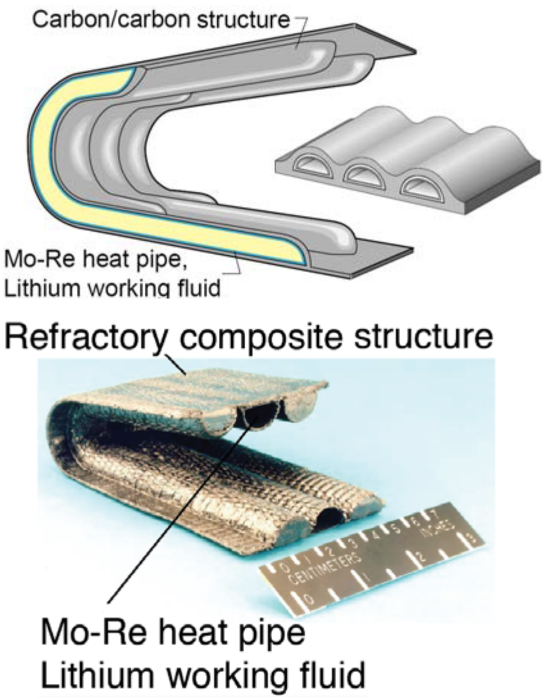

Figure 5. Shape and materials for heat-pipe-cooled leading edge

In 2007, Steeves [30] examined the feasibility of metallic leading edge heat pipes, made of Cb-752 and used Na as the working fluid, for hypersonic vehicles in Mach 7 flight. The heat pipes integrated within metallic leading edges provided very high effectively thermal conductivity which allowed heat to be transferred from the hot leading edge to large cool surfaces for radiation into space. Different materials were analyzed by Steeves [31]. Compared with Inconel 625 heat pipes used Na as working fluid, Cb-752 heat pipes used Li as working fluid have better thermal protection effect.

Chen [32-34] conducted experiments on heat pipes, used alkali metals as working fluid (see Fig. 6), for thermal protection system for hypersonic vehicle within the atmosphere. Compared with composite material, the stagnation point temperature was reduced by 9.5% and temperature at the contact position of the sphere and cylinder was reduced by 10.4%. And wall temperature at the position 130mm away from the stagnation point was increased by 14.6%. The results of experiments showed that heat pipes provided very high effectively thermal conductivity which allowed heat to be transferred from the hot stagnation region to cool surfaces. The feasibility of heat pipe used as heat-balance thermal protection for stagnation region of hypersonic vehicle was validated.

Figure 6. Photograph of high temperature heat pipe

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From 2009 to 2012, Liu [35-39] conducted numerical and experimental research on GH600 high temperature heat pipes, used Na as working fluid and embedded in C/C coating, for vehicle leading edge structure. Discontinuous Galerkin finite element method was used for thermomechanical coupling calculation to simulate heat transfer of high temperature heat pipe cooled thermal protection structure. Two way heat pipes distribution was designed to reduce the stagnation point temperature efficiently and to increase structure reliability greatly. When reserving assembly gap was used, contact stress on the structure interface would decrease observably while thermal contact resistance would increase which raised the stagnation point temperature. Experiments on high temperature thermal contact resistance between 3D braided C/C composite and high temperature alloy GH600 were conducted. The changing of thermal contact resistance with interface stress, interface roughness and interface temperature was obtained, which offered reference for design and safety evaluation on new high temperature heat pipe cooled thermal protection structure.

Due to the reported time, Table 2 is summarized.

Table 2. Heat-pipe-cooled leading edge for hypersonic vehicle

Time	Author	Working fluid	Container	Coating	Ref.
1966	Romano	Li	W	No coating	[3]
1978	Camarda	Na	Hastelloy-X	No coating	[12-14]
1988	Clark	Na	Haynes 25	Oxidation resistance coating	[19]
1990	Boman	Na	Hastelloy-X	No coating	[16-17]
1991	Wojcik	Li	Niobium Alloy	Oxidation resistance coating	[20-21]
1992	Busse	Li	W-Re	No coating	[40]
1994	Rovang	Li	-	C/C coating	[41]
1996	Merrigan	Na	Hastelloy-X	No coating	[18]
1992	Glass	Li	Mo-Re	C/C coating	[22-29]
2007	Steeves	Na	Cb-752	No coating	[30]
2009	Steeves	Na	Inconel 625	No coating	[31]
2009	Steeves	Li	Cb-752	No coating	[31]
2009	Chen	Alkali metals	-	No coating	[32-34]
2010	Liu	Na	GH600	C/C coating	[35-39]
2011	Qu	Na & Li	Niobium alloy	No coating	[42]

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

4 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/m^2 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 out, heat-balance thermal protection could be a good choice for thermal protection system. However, wall temperature should be lower than container melting point to prevent working fluid from leaking. Working fluid should be chosen according to working conditions to make sure part of working fluid remains liquid to keep working cycle going on.

Heat-pipe-cooled leading edge is used as heat-balance thermal protection for hypersonic vehicle [29]. It started to work when wall temperature is 2255K and the leading edge was nearly isothermal at 1870K. The heat pipes provided very high effectively thermal conductivity which allowed heat to be transferred from the hot leading edge to large cool surfaces for radiation into space.

5 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:

- Develop or choose new materials for container and working fluid;
- Develop or choose new materials for heat pipe coating;
- Design new structure for heat pipes;
- 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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