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Research Paper

An experimental investigation on transpiration cooling with phase change under supersonic condition

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HIGHLIGHTS

- High effect of transpiration cooling using water is verified in supersonic condition.
- Overcooling and ablation can be solved by controlling temperature and pressure of chamber.
- Zirconia TBC offers a quite effective protection for impermeable alloy.
- A numerical approach to estimate water consumption is introduced.

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ABSTRACT

The extremely high heat loads on hypersonic vehicles make great challenges for the research and development of more effective Thermal Protection Technique (TPT). Transpiration cooling using liquid coolant has been confirmed as a promising TPT, because the phase change of liquid can release a large amount of latent heat. An experimental investigation on transpiration cooling using water as coolant was conducted in the arc-heated wind tunnel of China Academy of Aerospace Aerodynamics (CAAA), with a free stream specific enthalpy, mass flow rate and Mach number of 2700 kJ/kg, 645 g/s and 4.2, respectively. The specimen used in this experiment, a nose cone, consists of two types of materials. One is sintered porous material in the leading edge region as transpiration cooling matrix, and the other is impermeable alloy with zirconia Thermal Barrier Coating (TBC). The thermodynamic and aerodynamic parameters in coolant chamber are controlled by a quantitative injector of coolant mass flow rate to prevent the phenomena of overcooling and ablation. Surface temperature distributions are captured by an infrared thermal imaging system (ITIS). This paper exhibits and analyzes some interesting experimental phenomena, including ice formation in high enthalpy environment, hysteresis of thermal balance due to TBC, and variations of surface cooling effectiveness. A numerical approach to estimate the water mass flow rate is introduced and the relative error referenced experimental results is analyzed.

1. Introduction

With the research and development of hypersonic vehicles, one of the most important challenges faced is extremely high aero-heating loads, especially for the structures with sharp edges, including the nose cone and leading edge of rudders and wings. According to Choi et al. [1], the heat flux on the leading edge of a scramjet engine with a Mach number of 10 can achieve 1053 MW/m^2, while at the stagnation point of the nose cap can exceed 1400 MW/m^2. As predicted by Reimer et al. [2], for a future large size vehicle, German Space Liner, if the leading edge is designed by a radius of 10 mm, the maximum temperature of such an uncooled structure during flight will go up to over 5000 °C. It is clear that this kind of thermal loads under such extreme conditions has been far exceeded the limits of the allowable temperatures of current all materials. Therefore, it is very important to develop more effective and active TPT.

According to the comparisons between different active TPTs, including convection cooling, film cooling and transpiration cooling [3,4], transpiration cooling is demonstrated to be one of the most effective TPTs to actively protect the hot structures from the extreme conditions, and is well recognized as a potential means for cooling rocket nozzles [5], reentry vehicles [6] and gas turbine blades [7], etc. In recent ten years, a large number of investigations on transpiration cooling performances have been carried out by numerical [8–10], experimental [11,12] and theoretical [13–15] approaches. According to the coolant type,

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these investigations can be basically divided into two kinds, which are heat sink dominated in gaseous cooling and latent heat dominated in liquid phase change cooling.

Through comparing the transpiration cooling effects between air, argon and helium for a scramjet application, Langener et al. [16] indicated that the main influencing parameters on cooling efficiency are the specific heat capacity and mass flow rate of gaseous coolants. The transpiration cooling investigation of Otsu et al. [19] indicated that heat transfer rate can be reduced to a considerable extent even by a small amount of gas ejection, but in contrast to this, this reduction amplitude of heat transfer rate falls gradually, when the gas ejection rate is further raised. Liu et al. [17,18] used gaseous coolants to conduct transpiration cooling experiments of a nose cone and a flat plate, and their results exhibited the similar conclusion that even a small amount of gaseous coolant can drastically reduce the heat transfer from hot flow to the specimen, and cooling effectiveness increases quickly with coolant injection rate, but this increment becomes smaller, when coolant injection rate increases further.

To overcome the limit of gaseous cooling effect and drastically enhance cooling effectiveness, another type of high-efficient transpiration cooling with liquid phase change has aroused investigators' concern in recent years. Wang et al. [20] used a cylindrical model as specimen to compare the overall cooling effects provided by gaseous and liquid media. Their comparisons indicated that at the same mass flow injection rate, the cooling effectiveness of liquid evaporation is much higher than that of gaseous cooling, especially in the leading region of the specimen. Using nose cone models made of porous material consisting of 91% Al_2O_3, Foreest et al. [21] quantitatively compared transpiration cooling effects between water and gaseous coolants, and their experimental results predicated that the cooling effectiveness using water as coolant is much higher than that of using gaseous coolants.

It is clear that liquid coolants can provide much higher cooling effectiveness than gaseous coolants due to the latent heat released in phase change process, but there is another challenge, that is how to control a transpiration cooling system performing. In the experiments of Foreest et al. [21], the temperature at the stagnation point was cooled down to 500 K, which was far below the allowable temperature of porous material 91% Al_2O_3. Wang et al. [22] conducted a mechanism experiment of transpiration cooling using purified water as coolant, and their experimental analysis predicated that there is an optimal coolant injection ratio, at which the driving force for the liquid transport through pores is minimal, but the average cooling effectiveness over transpiration cooling area can achieve a relatively high level. Zhao et al. [23] experimentally investigated the transpiration cooling of a wedged nose cone in the arc-heated supersonic free jet facility (ASFJF) of CAAA, with a free-stream Mach number of 2, a specific enthalpy of 1300 kJ/kg and a total mass flow rate of 2.286 kg/s. Their experiment successfully demonstrated how to control the surface temperature of the wedged nose cone by adjusting injection rates of liquid coolant.

In recent years, transpiration cooling using fuel has been applied to solve the overheated problems of the engines of hypersonic vehicles. However, due to the limited heat sink of fuel, the fuel-cooled approach is insufficient and costly, especially for the critical external structures, such as the nose cone, the leading edge of wings and rudders. As a result, transpiration cooling using water is becoming one of the most potential TPT [24]. However, the previous relevant experiments were carried out at much lower conditions than real hypersonic flights. This paper presents an experimental investigation on transpiration cooling with water phase change. A wedged nose cone is used as the specimen, which is made up of porous material and impermeable alloy sprayed with zirconia TBC. The experiments are carried out in the arc-heated wind tunnel FD04 of CAAA in Beijing, at free-stream Mach number of 4.2, specific enthalpy of 2700 kJ/kg and mass flow rate of 645 g/s. The aim of our work is to investigate the phase change behaviors during liquid transpiration cooling under supersonic conditions, to verify the practicability in hypersonic vehicles, and provide the investigators and designers of transpiration cooling systems with a relative comprehensive reference.

2. Experimental apparatus and specimen

2.1. Experimental apparatus

As shown in Fig. 1, the arc-heated wind tunnel system consists of six sections, i.e., arc heating section, mixing section, nozzle, test chamber, diffuser, heat exchanger and vacuum system. The operational process of the wind tunnel is basically concluded as followings. At first, the vacuum pump runs and makes the test chamber of wind tunnel in vacuum state, till the pressure is finally as low as about 2 kPa. The aim of the vacuum process is to create great pressure differentials, and to achieve high Mach number and simulate a real space flight environment thereby. Then the intake system of the wind tunnel is operated. A part of compressed air at ambient temperature is ejected from high-pressure tank, and turns into high temperature when flowing through the arc heating section and the mixing section. The arc heating effect makes the wind tunnel with lower Mach number can simulates a real hypersonic flight with a higher Mach number. Passing the nozzle, the gas flow with high temperature is accelerated to be supersonic up to a set Mach number. Hence, in the test chamber, the flow with high enthalpy and Mach number impinges the specimen, which is put on a bracket away from the nozzle outlet with 20 mm. At last, after a deceleration in diffuser and a cooling process in heat exchanger, the gas flows into the vacuum tank, and is finally released into atmosphere. The arc-heated wind tunnel FD04 of CAAA has a maximum electrical power supply of 30 MW, which can generate a maximal gas enthalpy of 25 MJ/kg and a Mach number up to 10, respectively. The maximum running time is up to 2000 s.

An infrared thermal imaging system (ITIS) is used to capture the surface temperature of the specimen. The ITIS has a measurement accuracy of ±1% RFS (Relative error in Full Scale). To calibrate the temperature measured by the ITIS and monitor the temperature at the leading edge, two monochrome thermometers with a higher accuracy of ±0.3%RFS are used to record the local temperature at the points of 5 mm and 15 mm away from the stagnation point along the centerline of the specimen surface. To detect liquid phase change process within the coolant chamber of specimen, a pressure transducer with an accuracy of ±0.5%RFS is installed at the inlet of coolant chamber, and two thermocouples with the same accuracy ±0.75%RFS are installed into coolant chamber. One thermocouple is near the stagnation point, and the other is near the inlet of coolant chamber. To monitor the dynamic state of free stream impinging the specimen and evaporation process of liquid coolant, two high-speed cameras are fixed on the outsides of two view-windows, from which the formation of shock wave and evaporating gas film can be recorded. All the data measured and phenomena monitored are collected to control center.

According to the previous theoretical analysis and experimental data [9,22], the transport performance of liquid coolant is different from that of gaseous coolant, due to coolant phase change. External high heat flux leads to liquid evaporation in coolant chamber, and the drastic change in coolant density results in a large pressure fluctuation. Water injection by a constant flow rate is more favorable than that by a constant pressure. Therefore, a quantitative injection pump with a maximum driving pressure of 2 MPa and an accuracy of ±0.5%RFS is used to ensure given mass flow rates of liquid coolant into the coolant chamber.