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Review

An experimental investigation on transpiration cooling of wedge shaped nose cone with liquid coolant

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ABSTRACT

During hypersonic flight in the terrestrial space, the heat flux loaded by some certain locations of vehicles, such as nose cone and combustion chamber, can reach very high values. Transpiration cooling has been recognized as one of the most effective technologies of heat dissipation to protect the vehicles from the very high heat flux. This paper presents an experimental investigation on transpiration cooling of the wedge shaped nose cone with an unequal thickness porous wall using liquid water as coolant. The experiments were performed in the heated gas wind tunnel at the University of Science and Technology of China (USTC), the surface temperature of the nose cone sample was measured by an infrared thermal imaging system, the pressure and temperature in coolant chamber were measured by a series of the transducers connected with a PC, to detect transpiration cooling effect and the driving force of the liquid water at different mainstream temperatures, Reynolds numbers and the coolant injection ratios. The experimental data indicated that the design of the unequal thickness walled nose cone is effective to solve the key issue of cooling stagnation point, there is an optimal coolant injection ratio, at which the driving force for the liquid transport through pores can achieve the minimum, and the average cooling effectiveness over total transpiration area is still at a relatively high level.

Contents

1. Introduction

The fast development of spaceflight and aviation technologies leads to the thermal loads of the components exposed in high heat fluxes increasing rapidly. For instance, the turbine inlet temperature of the Joint Strike Fighter Lighting II is about 3600°F [1]; when a hypersonic vehicle cruises with Mach number 6.5 at 28 km

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Nomenclature

T	temperature [K]
v	kinematic viscosity [m^2/s]
Nu	Nusselt number
h	convective coefficient [W/m^2 K]
η	cooling effectiveness
F	coolant injection ratio
u	velocity [m/s]
Re	Reynolds number
Pr	Prandtl number
k	heat conductivity [W/m K]
$\dot{m}$	mass flow rate [g/s]
D_h	hydraulic diameter [m]

Subscripts

c	coolant
iw	wall temperature without coolant
∞	hot mainstream
cw	wall temperature with coolant

altitude, its leading edge has to endure 1902 K temperature, with Mach number 8 at 32 km altitude, the maximal temperature in the combustion can achieve 3200 K [2]; it is inevitable that the total temperature of hypersonic vehicles increases with flight Mach number, at Mach number 8 and 10, the total temperatures are 2778 and 3889 K, respectively [3]. These aggressive environments have already far exceeded the allowable temperatures of currently advanced materials. Therefore, transpiration cooling as a most effective mechanism of heat dissipation has come to numerous investigators' attention, and the corresponding researches have been extended into different fields for both military and civil applications, such as the combustion chambers of scram-jet engines, the leading edges of hypersonic vehicles [4–6], the first stages of gas turbine blades [7–9], and rocket nozzles [10–12]. In China, the fundamental researches including new and efficient thermal protection technique, as a kind of reserve technologies to develop hypersonic vehicles, have been got more attention in recent years.

The experimental investigations on transpiration cooling can be classified into two groups, fundamental or mechanism research and confirmatory test. The earlier studies can be traced back to the Fifties of the last century, Rashis [13] investigated transpiration cooling of a double wedge using nitrogen and helium as coolant at Ma = 2.0. They found that the helium coolant is from four to five times more effective than nitrogen coolant. This ratio is approximately the same as the ratio of the heat capacities of helium and nitrogen. Chauvin et al. [14] used gaseous nitrogen and helium, as well distilled water as coolant to investigate the transpiration cooling performances of a sharp cone in a free jet with Mach number 2.05 and Reynolds number 8×10^6. Their investigation found that the transpiration cooling with water gave a larger reduction in average wall temperature with less water consumption than that with gaseous film cooling. In the latest studies, to detect the influences of the thermal property of coolant on transpiration cooling effect, Liu et al. [5] studied the cooling characteristics of an equal thickness walled nose cone using different gaseous media (air, N_2, He, Ar, CO_2), and their tests were performed within a mainstream temperature range of 375–425 K and Reynolds number from 4630 to 10,000. Langener et al. [15] carried out transpiration cooling tests at maximum wall temperature 670 K, and used a flat plate made of C/C porous material as specimen to quantify the effect of specific heat capacity of gaseous cooling media (air, He, Ar) on cooling effectiveness. Wang et al. [16,17] conducted transpiration cooling experiments to compare the features of liquid and gaseous cooling media at mainstream temperatures from 375 to 525 K and Reynolds number level 10^5, and their comparisons indicated that liquid evaporation cooling effectiveness is much higher than gaseous cooling at the same blowing ratios, especially in stagnation regions. The fundamental researches mentioned above were generally performed at much lower temperature and Reynolds number than the corresponding application conditions. It is clear that water as coolant has a large potential to resist very high heat fluxes due to the extremely high latent heat of vaporization (2257 kJ/kg at 1 atm), and the advantages of small volume per mass and convenient transport. To verify these advantages, van Foreest et al. [18] carried out a series of confirmatory test by nearly true conditions of hypersonic vehicles in DLR's Arc Heated Wind Tunnel, at Mach number 5.45, the wind-tunnel reservoir temperature 3028 K and enthalpy 4.3 MJ/kg. Their nose cone models were made out of 91% Al_2O_3 and 9% SiO_2, which is ability to withstand temperatures of up to 2000 K. However, their cooling effect resulted in the surface temperatures of the model lower than 500 K. It is clear that this was an overcooling phenomenon in comparison to the material's allowable temperature.

The fundamental investigations on the transpiration cooling characteristics with liquid phase change were conducted by improving mathematic model and numerical simulation [19,20]. The investigations indicated that when phase change appears within porous matrix, the temperature of solid matrix might increase rapidly, the vertiginous pressure of vapor could result in a counter flow of liquid coolant, and these phenomena could lead to solid matrix ablation.

To avoid the overcooling phenomenon appeared in the experiment and the ablation of solid matrix predicted by the fundamental investigation, a large number of mechanism experiments in relatively stable environment with a relatively low cost are still necessary, to help us understanding the relationship of liquid coolant flow rate, driving force of the coolant transport, phase change behavior and cooling effectiveness. This paper presented an experimental investigation on transpiration cooling with phase change of liquid coolant. The aim was to provide the mechanism investigators and engineering designers of transpiration cooling system with a relatively comprehensive reference.

2. Experiment apparatus and specimen

The experiments were carried out in the hot wind tunnel at the University of Science and Technology of China. As illustrated in Fig. 1, compressed air at ambient temperature was injected into the wind tunnel through three filtrations, in order to decrease the influence of the impurity on experimental results. The air flow rate entering into the wind tunnel was dominated by a digital mass flow rate controller, to achieve a certain mainstream velocity or Reynolds number. The injected air was heated by a series of electrical resistance heaters with a maximal temperature limitation of 1600 K. This heating process was accurately controlled by a digital temperature control system, to provide a certain mainstream temperature, and the accuracy of the control system could achieve ±1 K. The heated air flow entered into a rectangular passage with a hydraulic diameter of 50 mm (46×54 mm^2), then discharged from the rectangular passage. The specimen was installed at 6 mm far from the outlet section of the rectangular passage. Two