International Journal of Thermal Sciences 84 (2014) 207–213

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

An experimental investigation on transpiration cooling under supersonic condition using a nose cone model

Lianjin Zhao [a], Jianhua Wang [a,*], Jie Ma [a], Jia Lin [a], Jinlong Peng [b], Dejun Qu [b], Lianzhong Chen [b]

[a] University of Science and Technology of China, Hefei 230027, Anhui, PR China
[b] China Academy of Aerospace Aerodynamics, Beijing 10074, PR China

ARTICLE INFO

Article history:
Received 9 October 2013
Received in revised form
6 May 2014
Accepted 7 May 2014
Available online

Keywords:
Transpiration cooling
Nose cone
Supersonic experiment
Ice formation
Shock wave
Unequal thickness walled configuration

ABSTRACT

During hypersonic flight or cruise in the near space, the aerodynamic heating created very high heat flux onto the leading edge of hypersonic vehicles. Transpiration cooling has been recognized the most effective cooling technology, due to its large specific surface of heat convection and active cooling mechanism through heat exchange between coolant and porous matrix. This paper presents a supersonic experimental investigation on transpiration cooling of a nose cone model with unequal thickness walled configuration using liquid water as coolant. The experiments were conducted by the Arc-heated Supersonic Free Jet Facility (ASFJF) of the China Academy of Aerospace Aerodynamics (CAAA) in Beijing. To detect cooling effect, the surface temperature of the nose cone was measured by an infrared thermal imaging system, and the pressure and temperature in coolant chamber were recorded by a series of transducers connected with a PC. The experimental data indicated that at mainstream Mach number 2.0, stagnation pressure 173 kPa and mass flow rate 2.286 kg/s with enthalpy 300 kJ/kg, ice cake appeared at the nose cone surface, but the ice cake disappeared when the stagnation pressure and the enthalpy rise to 305 kPa and 1300 kJ/kg, respectively. The design of the unequal thickness walled configuration nose cone is effective to solve the key issue of cooling stagnation point. The cooling effectiveness at the different regions of the nose cone was analyzed, and shock wave was exhibited.

1. Introduction

During hypersonic flight or cruise in the near space, the aerodynamic heating caused by high Mach numbers and the shock wave impingement on the leading edges of an aircraft create very high heat flux, which imposes severe demands on more active and effective thermal protection technologies, especially for the wedge-shaped nose cone of the aircraft. The high surface temperatures corresponding to the high heat flux can exceed all melting points of conventional metallic and potential ceramic materials available for aerospace applications today. For example, when a hypersonic vehicle cruises with Mach number 6.5 at 28 km altitude, its leading edge has to endure 1902 K temperature; and the total temperature of the hypersonic vehicles increases with flight Mach number, at Mach number 8 and 10, the total temperatures can achieve to 2778 and 3889 K, respectively [1]. The leading edge radius has a significant impact on the heat flux [2,3]. For example, the heat flux to a leading edge of 2 inches radius of curvature on a hypersonic vehicle flying at Mach 10 at 30 km is approximately 200 W/cm^2. If the radius of curvature of the leading edge is reduced to 0.25 inches, the heat flux becomes approximately 500 W/cm^2 [4]. Therefore the development of more effective thermal protection technique is the key issue and also a significant challenge for the investigators of hypersonic and re-entry vehicles.

Transpiration cooling has been recognized the most effective cooling technology, due to its large specific surface of heat convection and active cooling mechanism, as shown in Fig. 1. Fluid coolant is injected into porous matrix in the direction opposite to heat flux [5], at the same time absorbs the heat conducted into the solid matrix and transports heat flux through the convection passing pores, as like a counter flow heat exchanger, finally, the coolant forms a thin film on the hot side surface to reduce the heat flux coming into the porous matrix.

There have been a large number of research literature regarding the leading edge transpiration cooling of the hypersonic vehicles through theoretical, numerical and experimental approaches

* Corresponding author. Tel.: +86 55163600945.
E-mail addresses: zlj@mail.ustc.edu.cn (L. Zhao), jhwang@ustc.edu.cn (J. Wang).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.05.019
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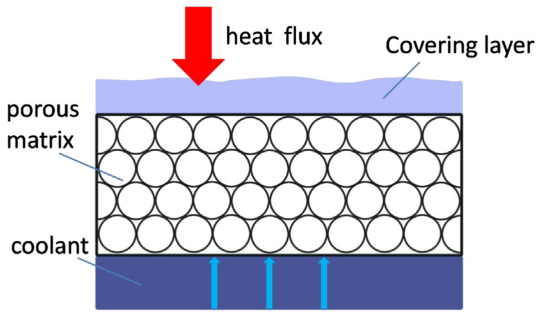

Fig. 1. Principle of transpiration cooling.

[5–9]. In the experimental aspect, the previous investigations can be classified into two groups, according to coolant types, i.e. gaseous and liquid coolant. Using different gases (air, N_2, He, Ar, CO_2), Liu et al. [10] carried out a series of experiments to investigate transpiration cooling characteristics of a blunt nose cone. Through experiments and numerical simulation, Jia [11] studied air cooling performances of a hemispherical blunt cone, which consists of sintered porous super-alloy. Langener et al. [12] used carbon/carbon (C/C) material to manufacture four flat plat samples, and compared the transpiration cooling effects of gaseous argon, helium (Ar, He) and air in a subsonic wind tunnel, Mach numbers between Ma 0.3 and 0.7, while total temperatures of up to 523 K. Using gaseous N_2, Hirotaka et al. [13] conducted transpiration cooling tests to investigate heat transfer rate of a cylindrical nose cone made of sintered alumina particles at mainstream enthalpy 14 $\pm$ 0.5 MJ/kg and impact pressure 1.5 $\pm$ 0.03 kPa, their experimental results indicated that even a small amount of gas ejection can reduce the surface temperature and heat transfer rate considerably, while the surface temperature and heat transfer rate decreases only gradually as the gas ejection rate is further raised, because a coolant mass flux of 0.02 kg/m^2 s could reduce the surface temperature from 1650 K to 1500 K, but the surface temperature only reduced to 1400 K even though the gaseous mass flux was raised to 0.2 kg/m^2 s. That is to say, the transpiration cooling effect of gaseous coolant is limited.

To break through the limitation of gaseous coolant, liquid coolant as a potential candidate has been considered in the last few years. Bellettre et al. [14,15] used a sintered stainless steel flat plate as specimen to quantify the cooling effects of different cooling media including air, water vapor of 373 K and liquid alcohol. Their experiments revealed that the transpiration cooling using liquid coolant is more effective compared to using gaseous coolant, because the cooling effectiveness can be more than 95% while the effusion rate of liquid alcohol is only about 2% of the gaseous coolant. Wang et al. [16,17] conducted a series of transpiration cooling experiments using two cylindrical specimens at mainstream temperatures from 375 to 525 K and Reynolds number level 10^5, to compare quantitatively the cooling features of liquid water and gaseous air. Their comparisons indicated that the liquid cooling effectiveness is much higher than that of gaseous medium at the same blowing ratios, especially in the stagnation regions of the cylindrical specimen. It is clear that liquid coolant has a much higher cooling capacity per unit mass due to the large latent heat released by liquid phase change, which can achieve 2257 kJ/kg (1 atm). To verify the advantages of liquid water for the future hypersonic vehicles, Van Foreest et al. [18] carried out a series of verification tests in the DLR's Arc Heated Wind Tunnel, at a Mach number of 5.45, wind-tunnel reservoir temperature of 3028 K and enthalpy of 4.3 MJ/kg. Three nose cone specimens with radius 1 cm, 1.75 cm and 2.5 cm were made of 91% Al_2O_3 and 9% SiO_2. Their experimental data concluded that the transpiration cooling of the radius 2.5 cm nose cone with 0.2 g/s liquid water can result in a surface temperature drop of the specimen from higher than 2000 K to lower than 500 K. This surface temperature is much lower than the material's allowable temperature of the specimen, and when with excessive water injection rate a large ice block appears. To deeply study liquid transpiration cooling phenomenon, Thomas Reimer et al. [2] conducted a new series of tests with a flat disk oriented normal to the direction of mainstream from the LBK (Lichtbogen Beheizte Windkanal) facility in Cologne, the cooling effect was not very significant, the reason was deemed that probably ice formation blocked the transport of water, and resulted in water flow rate insufficient. But in the next research, they gave a medium value of the lower limit mass flow 0.33 g/s at a pressure of 225 hPa which is equal to 0.152 kg/m^2 s at approximately 1 MW/m^2 heat load with flat samples [19]. This provides a reference absolute number of required coolant per area and time unit for the researchers engaged in similar work.

The fundamental investigations on the transpiration cooling characteristics with liquid phase change were carried out by improving mathematic model and numerical simulation in our previous studies [8,20]. The numerical results indicated that when phase change appears within porous matrix and near hot side, the temperature within the solid matrix might increase rapidly, the vertiginous pressure of water vapor could result in a counter flow of liquid coolant, and these phenomena could lead to solid matrix ablation.

It is a significant challenge, how to avoid overcooling phenomenon, i.e. the porous matrix temperature is far lower than the allowable temperature, ablation phenomenon (existing in our previous simulations), and blocking coolant effusion of ice cake (existing in the hypersonic wind tunnel tests) due to low pressure environment caused by vacuum. To solve these problems, an experimental investigation on the transpiration cooling with liquid phase-change was conducted by an open supersonic wind tunnel, the Arc-heated Supersonic Free Jet Facility (ASFJF) of China Academy of Aerospace Aerodynamics (CAAA) in Beijing. The experiments were carried out with two conditions, one is at a mainstream Mach number of 2.0, mass flow rate 2.286 kg/s with enthalpy 300 kJ/kg, stagnation pressure 173 kPa, and the other is at the same Mach number, mass flow rate, but the stagnation pressure and the enthalpy rise to 305 kPa and 1300 kJ/kg, respectively. Three coolant flow ratios $F = 0.27$, 0.24 and 0.19% were injected into the test model, the corresponding cooling effectiveness and shock wave variations were analyzed. The aim of this work is to exhibit the cooling performances of the nose cone with an unequal thickness walled configuration using liquid coolant at a supersonic condition, to study coolant injection pressure of transpiration cooling system, and to provide a relatively comprehensive reference for the investigators and designers of the thermal protection systems of hypersonic vehicles.

2. Experimental apparatus and test model

2.1. Arc-heated Supersonic Free Jet Facility and measuring equipments

The transpiration cooling experiments were performed in the ASFJF of CAAA. A schematic view of the ASFJF is shown in Fig. 2. A part of compressed air at ambient temperature was injected into the arc-heated segment, and heated by plasma arc. This process generated a high enthalpy and high pressure gas flow, which was