International Journal of Heat and Mass Transfer 127 (2018) 882–891

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimization transpiration cooling of nose cone with non-uniform permeability

Nan Wu [a], Jianhua Wang [a,*], Fei He [a,*], Liang Chen [b], Bangcheng Ai [b]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Jinzhai Road 96, Hefei 230027, PR China
[b] China Academy of Aerospace Aerodynamics, Beijing 100074, PR China

ARTICLE INFO

Article history:
Received 27 February 2018
Received in revised form 20 June 2018
Accepted 25 July 2018

Keywords:
Optimization transpiration cooling
Non-uniform permeability
Nose cone
Cooling effectiveness
Coolant allocation

ABSTRACT

With the development of active thermal protection techniques (TPTs), optimization transpiration cooling (OTC) design, to enhance the cooling effect in stagnation regions and decrease coolant load, has become a critical issue in the research and development of hypersonic vehicles. One of the possible OTC approaches is using a non-uniform porous material to vary the coolant allocation within pores. This paper presents an experimental and numerical investigation on the transpiration cooling performances of two wedge shaped nose cones. One is for OTC, made of a special porous matrix with non-uniform permeability to ensure the largest porosity near the stagnation point, and the other is for traditional transpiration cooling (TTC), consisting of a general uniform porous matrix. Surface temperature and cooling effectiveness of the two nose cones are investigated in the experiments. The data show that in comparison with TTC, OTC can effectively enhance the cooling effectiveness in stagnation regions through a locally high permeability, and improve the uniformity of the temperature distribution within the entire nose cone. To exhibit the coolant flow characteristics within the pores, two-dimensional numerical simulations are carried out by commercial software FLUENT, and the numerical method is validated by the experimental data. The numerical results indicate that OTC with non-uniform permeability can provide an optimized coolant allocation and decrease the driving force required by the coolant transport to the stagnation region.

1. Introduction

With the development of near space hypersonic vehicles and fully reusable launch vehicles, the efficiency and sustainability of active thermal protection techniques (TPTs) has gradually become a hot topic for the structures loaded by extremely high heat flux, such as the nose cones of the vehicles, the leading edges of wing and rudder [1,2].

The earlier studies have predicted that transpiration cooling is a more effective TPT in comparison with the convection cooling and film cooling [3,4], because transpiration cooling is based on the porous matrix, which has a large area ratio of convective heat transfer. The recent experiments of cooling leading edges, which were conducted in the supersonic arc heating wind tunnel of DLR [5,6] in Germany, and with a controllable liquid injection system in the supersonic arc heating wind tunnels of CAAA [7,8] in China, all exhibited the excellent and high-efficiency characteristics of the transpiration cooling with liquid coolant. However, these experimental studies on the transpiration cooling performances were carried out by the uniform porous matrix, and therefore the cooling effectiveness at the stagnation point was deservedly the lowest, conversely, where the aerodynamic heating and pressure is the highest. In this background, the aim of optimization transpiration cooling (OTC) is in front of us. The core idea of OTC is to search for a better design, which can meet the requirement of a targeted coolant allocation [9].

Currently, OTC schemes can be classified into two broad categories according to varying transpiration cooling structures. One is to change the macro-structures, for example, varying wall thickness of the porous matrix, adding coolant chambers or pre-drilling film holes, and the other is to manipulate the micro-properties of the porous matrix. Wang et al. [10] conducted a series of transpiration cooling experiments with an unequal-thickness wedge shaped nose cone, the leading edge of the nose cone is the thinnest in their porous matrix, and their experimental data exhibited the feasibility of the unequal-thickness nose cone. Huang et al. [11] and Jiang et al. [12] studied the coolant injection performances with a multi-chamber design, and the combined effect of transpiration and film cooling via pre-drilled holes at the leading edge. Their results indicated that these designs could effectively cool the entire specimens, and distribute more coolant into a higher aerodynamic heating zone. Brune et al. [13,14] numerically studied a saw-tooth wall velocity distribution and designed a prototype

* Corresponding authors.
E-mail address: jhwang@ustc.edu.cn (J. Wang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.134
0017-9310/

Nomenclature

a_{sf}	specific surface area, m^2
c_p	specific heat, J/(kg K)
d_p	particle diameter, m
F	coolant injection ratio
h_{sf}	heat transfer coefficient, W/(m^2 K)
K	permeability, m^2
L	length of porous part, m
m	mass flow rate, kg/s
$\dot{m}$	mass flux, kg/(m^2 s)
P	pressure, Pa
T	temperature, K
u	velocity, m/s
x	distance from the leading edge, m

Greek symbols

ε	porosity
η	cooling effectiveness
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa/s
ρ	density, kg/m^3

Subscripts

c	coolant
cw	wall temperature with coolant
eff	effective
f	fluid phase
iw	wall temperature without coolant
s	solid phase
∞	mainstream

Abbreviations

ITIS	infrared thermal imaging system
OTC	optimization transpiration cooling
TTC	traditional transpiration cooling

transpiration nose cone, which has a tailored porosity and various thickness prescribed at the manufacturing level to produce a variable blowing profile. To improve the local cooling effect, Shen and Wang [15] proposed a new design using non-uniform porosity matrix along the mainstream direction, and numerically validated the superiority of this design under supersonic condition with a freestream total temperature of 2310 K and a freestream Mach number of 4.2. To better solve the problems of the heat transfer deterioration due to locally high heat flux, Dong and Wang [16] numerically studied and compared three OTC approaches, i.e., varying local porosity and thermal conductivity, adding separating wall to generate multi-chamber, and varying the wall thickness of porous matrix. Their numerical results demonstrated that the approaches of varying local porosity and adding coolant chambers are more effective for solving the problems of local heat transfer deterioration, and the highest temperature at the hot side through the two approaches can be decreased by approximately 40% and 55%, respectively.

In brief, the macro-structures optimization is flexible, but is usually limited by the scales of leading edge and the channel design of chambers, and therefore OTC design through non-uniform micro-property may be a preferred strategy. However, up to now, most of the researches on non-uniform micro-property are limited within the numerical stage [15,16], and the corresponding experimental data are quite lacking.

This paper presents an experimental and numerical comparison of transpiration cooling between two wedge shaped nose cones, one is made of a special porous material with a non-uniform permeability, i.e., the permeability in the stagnation region is the highest and then falls in the downstream, and the other is made of a uniform porous material to reflect traditional transpiration cooling (TTC). The aim of this work is to provide the investigators and designers of active TPTs with a relatively comprehensive reference, including the experimental feasibility of OTC design with non-uniform porous material and the cooling mechanism.

2. Experimental investigation

2.1. Apparatus

The experiments are conducted in the electric-heating wind tunnel at the University of Science and Technology of China (USTC). As shown in Fig. 1, the compressed air at ambient temperature is injected into the wind tunnel through three filters. To achieve a certain mainstream velocity, the air flow rate is controlled by a digital mass flowmeter. Then the injected air is heated by three series of electric resistance wires, and the heating process is accurately controlled by a digital temperature system with an accuracy of ±1 K. Through a heating section, the heated air flow passes through a rectangular passage with a hydraulic diameter of 46 mm (34 mm × 70 mm), and finally discharges from the rectangular passage. The specimen is installed near the outlet of the wind tunnel. Cooling air at ambient temperature is injected by another compressor, and the air flow injection ratios are exactly controlled by another digital mass flowmeter with an accuracy of ±2% RFS.

The inlet temperatures of the mainstream are measured by two thermocouples, and the temperature near the cold side of the porous matrix is measured by another thermocouple. These thermocouples are made by Fangta Temperature Instrument Company in Shanghai with the same accuracy of ±0.75%. The surface temperature of the specimen is captured by an infrared thermal imaging system (ITIS), NEC TH5104R, with a temperature resolution of ±0.1 K. The infrared window is made of sapphire glass, and its transmissivity in the wavelength range of 2–12 μm is 85%.

2.2. Test specimen

Two specimens with the same geometry are designed and manufactured, one is for optimization transpiration cooling (OTC), and the other is for traditional transpiration cooling (TTC). As illustrated in Fig. 2, each specimen of the wedge shaped nose cone consists of two parts, the leading edge made of a porous matrix, and the other part as coolant chamber manufactured by impermeable stainless steel. The leading edge has an external radius of 5 mm, an inner cone angle of 12°, a constant thickness of 2.5 mm and a total length of L = 15 mm in the x-direction. The two parts are welded together to guarantee the sealing.

The difference between the two specimens is the porous material property. For OTC, the porous leading edge consists of three layers, i.e. layer A (x/L = 0–0.26), B (x/L = 0.26–0.52) and C (x/L = 0.52–1), and permeability in layer A is the highest. Here, x represents the curvilinear abscissa following the specimen external boundary. For TTC, the porous matrix is uniform and its permeability is the same of layer C.