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An experimental investigation on combined sublimation and transpiration cooling for sintered porous plates

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ABSTRACT

To enhance the cooling effect in stagnation regions, a combined cooling method of sublimation and transpiration through locally activating transpiration was proposed and experimentally evaluated in the hot gas wind tunnel at the USTC. This combined cooling was achieved by sublimating an impermeable coating layer of low sublimation point material. The sintered porous plate used in this experiment consists of nickel-based super alloy with a porosity of 0.33, and Teflon is used as sublimation coating material. The cooling performances of the combined cooling method were compared with traditional transpiration cooling. The experimental data indicate that: (1) the coating layer sublimation mainly happens in the upstream and provides a flexible way to locally activate transpiration cooling, which means that where heat flux is the highest, the transpiration cooling is locally activated. (2) The combined cooling can effectively solve the problem of extremely high heat flux in stagnation regions, and reduce the consumption of transpiration coolant. Under the conditions of this experiment, at a coolant injection ratio of 0.60%, the cooling effectiveness at the leading edge of the specimen is 63% higher in comparison with traditional transpiration cooling. (3) The uniformity of temperature distribution can also be achieved by adjusting coolant mass flow rate for the combined cooling.

1. Introduction

Transpiration cooling has been demonstrated as one of the most promising methods of heat dissipation to protect hypersonic vehicles from extremely high heat fluxes [1–5]. It is clear that the transpiration cooling using liquid coolant is more effective than that using gaseous coolant, due to the latent heat released in phase change [6–8]. Therefore, the transpiration cooling with liquid phase change has aroused researcher's concern [9–13] recently.

Though the transpiration cooling with liquid phase change exhibits excellent cooling performances, it has some rooms for improvement, for example, the cooling effectiveness at the stagnation region of hypersonic vehicles is always the lowest, because where the aerodynamic heating and pressure are the highest. Therefore, it is necessary to locally increase the coolant mass flow rate in the stagnation region.

Zhao et al. [14,15] investigated the transpiration cooling performances using an unequal thickness porous matrix as wedge shaped noses, in a low-speed high-temperature wind tunnel and an electric arc heated supersonic free jet facility, respectively. Their results indicated that the design of the unequal thickness is effective for solving the cooling issues of stagnation points. Similarly, with an unequal thickness design, Shen et al. [16] conducted a transpiration cooling experiment using liquid coolant under a very harsh condition, at free-stream Mach number, specific enthalpy and mass flow rate of 4.2, 2700 kJ/kg and 645 g/s, respectively. This experiment successfully demonstrated that the surface temperature can be controlled by adjusting coolant mass flow rates. However, in these experiments, the cooling effectiveness in the stagnation region was still the lowest. Guill et al. [17] chose a saw-tooth velocity profile of coolant to represent a variable-transpiration strategy, and the variable transpiration cooling reduced the heat flux at stagnation point by an additional 8% in comparison with uniform transpiration. Jiang et al. [18] conducted transpiration cooling experiments using three struts in a supersonic wind tunnel, and liquid coolant was injected into two separated cavities by two independent pipes. Their results indicated that the transpiration cooling with non-uniform coolant injection could effectively cool the entire strut, and distribute more coolant to the front higher aerodynamic heating zone.

This paper suggests a new cooling concept, i.e. the combined cooling of sublimation with transpiration. As shown in Fig. 1, the porous matrix exposed to a heat flux is coated by a type of

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Nomenclature

F	coolant injection ratio
$\dot{m}$	mass flow rate [g/s]
T	temperature [K]
V	volume flow rate [m^3/s]
η	cooling effectiveness
ρ	density [kg/m^3]

Subscripts

c	coolant
∞	main stream
cw	wall temperature with coolant
iw	wall temperature without coolant

sublimation material, and the sublimation point is lower than the use temperature of the matrix. The main advantages of the sublimation active cooling are concluded as followings:

(1) The pores on the matrix surface are closed, when the surface temperature is lower than the sublimation point, therefore the coating layer can avoid the dust blockage coming from the mainstream and coolant leakage before active transpiration cooling system operation.
(2) Once the coating layer in the region with higher heat flux is sublimated, the transpiration cooling is locally activated, and coolant effusing from the pores forms a thin coverage film, thus the local cooling effectiveness in this region will be well enhanced.
(3) Compared with the cooling designs on the leading edge such as pre-drilled holes or non-coated surface [19], the combined cooling technique of sublimation and transpiration is a kind of self-adapting thermal protection methods which can actively search for the position impinged by the highest heat flux, and effuse coolant to cool this position at first. Then the combined cooling can flexibly effuse coolant from different angles (the angle of drilled hole is predesigned and impossible to be adjusted), therefore it is more useful when the attack angle or the location of shock/shock varies. Besides, the thickness of ablated coating layer is very small, and the vapor layer caused by liquid coolant phase change is enough to balance the aerodynamic configuration.

This is a novel cooling conception, and the aim is to solve the issues of intelligently locally activating transpiration and enhancing the cooling effectiveness in the stagnation region. This paper exhibits a feasibility experiment to investigate the cooling performances of the new cooling method.

2. Experimental procedure

2.1. Experimental apparatus and specimen

The feasibility experiment was conducted in the open low-speed heated wind tunnel at the University of Science and Technology of China. A schematic view of the wind tunnel system is shown in Fig. 2. The compressed air at ambient temperature is injected into the wind tunnel through three filters. The air flow rate entering into the electric heating section is dominated by a digital mass flow rate controller, and the heating temperature is fixed by a digital temperature controller with a precision of ±1 K. Through a contraction section, the heated air flow accelerates and passes into a rectangular passage with a size of 80 × 26 mm, and finally jets from the outlet of the rectangular passage.

The specimen used in this experiment is set near the outlet. As shown in Fig. 3, it consists of three parts, sintered porous plate with coating layer, coolant chamber and solid frame. The sintered porous plate with a thickness of 8 mm and an effective transpiration area of 56 mm × 32 mm is made of nickel-based super alloy powders (73.46%Ni, 17.3%Cr, 7.5%Fe, 1.7%Si and 0.04%C) with an average diameter of 100 μm. The solid frame made of high temperature alloy 310S is connected with the coolant chamber and porous plate by bolts and a high temperature gasket.

The hot air temperature is measured by two thermocouples. To detect the phase change process of liquid water, a pressure sensor and two thermocouples are installed in the coolant chamber. One thermocouple monitors the chamber temperature and the other measures the bottom temperature of the plate. The thermocouples and pressure sensor are linked by a data acquisition card installed in a PC. The thermocouples are made by Fangta Temperature Instrument Company in Shanghai with an accuracy of ±0.75%.The surface temperature of the porous plate is recorded by an infrared

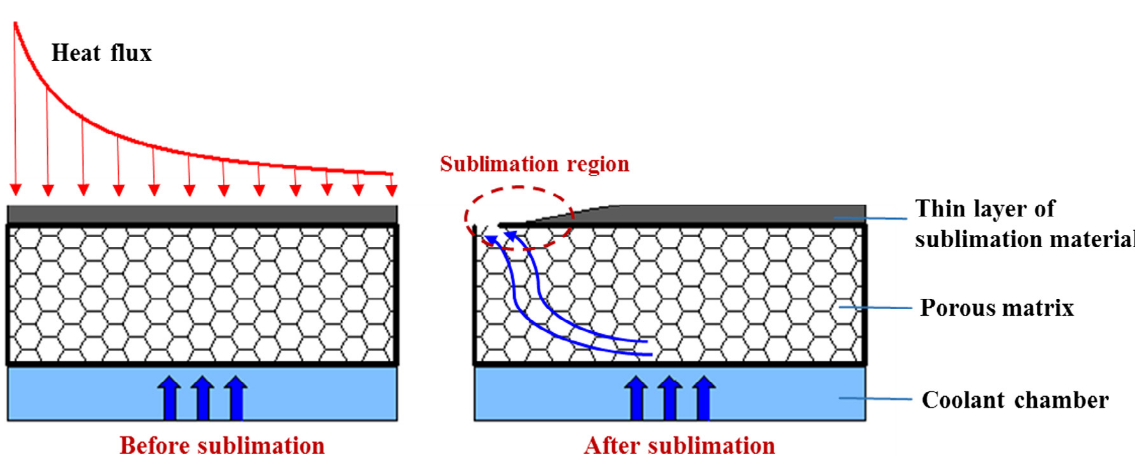

Fig. 1. A new cooling conception of combined transpiration with sublimation.