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# Experimental investigation of combined transpiration and film cooling for sintered metal porous struts

Pei-Xue Jiang [a], Gan Huang [a], Yinhai Zhu [a,*], Zhiyuan Liao [a], Zheng Huang [b]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Tsinghua University, Beijing 10084, People's Republic of China
[b] China State Shipbuilding Corporation, Haidian District, Beijing 10084, People's Republic of China

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ABSTRACT

A combined transpiration and film cooling method was evaluated experimentally for protecting struts made of sintered stainless steel porous media with film holes on the leading edge in a supersonic wind tunnel. The combined cooling results were compared to standard transpiration cooling of the strut. Schlieren figures show that the film cooling and transpiration cooling had little effect on the flow field stability and the shock wave profiles around the struts for the present conditions. Standard transpiration cooling can protect most of the strut but cannot effectively cool the leading edge even with increased coolant injection pressures. The combined film and transpiration cooling effectively cools both the leading edge and other parts of the strut. Non-uniform coolant injection with higher injection pressures in the front cavity and lower injection pressures in the back cavity more effectively utilized the limited coolant flow. The average cooling efficiency of the front part of the strut increased from 25.7% for standard transpiration cooling to 37.9% for combined transpiration and film cooling with the same coolant consumption using the optimal non-uniform coolant flow distribution.



## 1. Introduction

The supersonic combustion ramjet engine is a key part of air-breathing hypersonic vehicles [1]. The X51 reached Mach 5 for about 200 s in a recent test by the U.S. Air Force [2,3]. The hydrocarbon or hydrogen fuels have been directly injected into the combustion chamber by wall injectors [4,5] or strut injectors [6–8]. The strut injectors improve the combustion and the fuel and air mixing [7,9,10]. Masuya et al. [8] experimentally investigated ignition and combustion in scramjet combustors with five different fuel injection struts. They found that a more flow-disturbing strut improved the mixing and combustion. Gerlinger et al. [7] found that the strong streamwise vorticity created by a lobe shaped strut enhanced the hydrogen and air mixing. The strut geometry influenced the strength and size of the vortices. Liu et al. [11] experimentally investigated the influence of strut structures on enhancing the mixing and combustion in a supersonic combustion test facility. The combustion efficiency was increased 15.1% when the strut height was increased from 10 mm to 30 mm.

Strut injectors have many advantages compared to wall injectors. However, struts, especially the leading edges, experience severe aerodynamic heating and radiative heating in the scramjet combustion chamber with the high speed, high temperature main flow. Thus, the thermal protection of the struts is very important, but there have been few studies of the strut thermal protection. Simsont and Gerlinger [6] numerically investigated regenerative cooling of a lobe-shaped strut. The cold gaseous hydrogen flowed through a circuitous internal channel to cool the strut and was then sprayed into the combustion chamber through the strut trailing edge. Aerodynamic heating caused a high temperature region on the leading edge. The reflected oblique shock waves hitting the strut trailing edge resulted in a very high temperature region. Regenerative cooling protected most of the strut at low Mach numbers. However, the fuel flow would be insufficient to provide a sufficient heat sink for regenerative cooling at high flight Mach numbers and heat loads [12]. Chandrasekhar et al. [13] experimentally investigated different high temperature resistant materials for strut injectors. Materials with high heat capacities and low thermal conductivities were selected for passive cooling due to the limited coolant mass flow rate. However, the strut leading edge was eroded by the tremendous heat loads. The erosion of a Niobium C-103 alloy strut leading edge was more severe than for W-Ni-Fe alloy strut. Sun and Zheng [14] numerically investigated the thermal protection of struts made of a C/SiC composite with regenerative cooling. Their results showed that the coolant flow was not

* Corresponding author at: Department of Thermal Engineering, Tsinghua University, Beijing 100084, People's Republic of China.
*E-mail address:* yinhai.zhu@mail.tsinghua.edu.cn (Y. Zhu).

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**Nomenclature**

| | |
|---|---|
| $b$ | averaged blowing ratio |
| $L$ | horizontal length [mm] |
| $l$ | actual length along the surface [mm] |
| $M$ | mass flow rate [g/s] |
| $Ma$ | mach number |
| $P$ | pressure [Pa] |
| $T$ | temperature [K] |
| $V$ | velocity [m/s] |
| $x$ | distance from the strut leading edge [mm] |
| *Greek symbols* | |
| $\gamma$ | specific heat ratio |
| $\varepsilon$ | porosity |
| $\eta$ | cooling effectiveness |
| $\lambda$ | thermal conductivity [W/(m·K)] |
| $\rho$ | density [kg/m$^3$] |
| *Subscripts* | |
| b | back cavity of the strut |
| $C$ | coolant |
| f | front cavity of the strut |
| $W$ | wall |
| $\infty$ | main stream |

enough to cool the strut at a Mach number of 8. Therefore, more effective thermal protection methods are needed.

Transpiration cooling has been used to protect high heat flux surfaces, such as the nosecones of supersonic vehicles [15–18]. The coolant flows through a porous heated wall with the coolant efficiently absorbing heat from the porous media due to the numerous micro pores in the porous media with a protective film then formed on the porous media surface after the coolant flows out of the porous media [19,20]. Langener et al. [21] experimentally investigated transpiration cooling of composite carbon/carbon materials (C/C). Their results showed that the coolant specific heat capacity significantly influenced the transpiration cooling efficiency and that helium was more effective than air at the same mass flow rate. Zhao et al. [22] experimentally investigated transpiration cooling of a sintered metal porous nosecone using liquid water as the coolant with phase change in a heated supersonic free jet facility. Their results showed that the transpiration cooling was very efficient using liquid water as the coolant. The constant mass flow rate was more reasonable than with a constant injection pressure. Transpiration cooling has also been used to protect struts in scramjet combustion chambers in recent studies [23–25]. The numerical results of Huang et al. [24] and Xiong et al. [25] showed that the strut leading edge experienced the highest temperature. Huang et al. [23] experimentally investigated transpiration cooling of sintered stainless metal porous struts using methane as the coolant in a 60 s wind tunnel test with a Mach number of 2.5, a total pressure of 1.46 MPa and a total temperature of 1774 K. Their results also showed that the transpiration cooling effectively protected most of the strut with the strut leading edge having some ablation due to the tremendous aerodynamic heating.

Film cooling has been widely used to protect the leading edges of gas turbine blades [26–29]. In film cooling, the coolant flows through discrete film holes drilled into the gas turbine blades to form a protective film on the blade surface. Cruse et al. [30] experimentally investigated the influence of leading edge geometries, free stream turbulence levels and coolant to mainstream density ratios on leading edge film cooling. Liu et al. [31] experimentally investigated leading edge film cooling with three rows of film holes on a gas turbine blade to show that the film cooling efficiency increased with increasing blowing ratio. The mainstream Mach number had a slight effect on the film cooling efficiency on the pressure side with the film cooling efficiency decreasing with increasing Mach number on the suction side. Kim and Kim [32] experimentally investigated the influence of the holes structures on the leading edge film cooling efficiencies. Inclined holes had better film cooling efficiencies than other shapes. The film cooling efficiency near the injection holes was significantly higher than far from the film cooling holes.

Previous investigations have shown that transpiration cooling alone cannot effectively cool the leading edge of a porous strut. Film cooling could effectively cool the leading edge, but the cooling efficiency far from film holes was too low. This study further investigated combined transpiration and film cooling to protect struts. The struts made of sintered stainless steel porous media with three different strut structures were tested in a supersonic wind tunnel. The influences of the strut structures, coolant mass flow rates and non-uniform injection conditions on the cooling efficiencies and flow fields were experimentally studied.

## 2. Experimental system

### 2.1. Test facility

Fig. 1 shows the supersonic wind tunnel system used to investigate the combined cooling method for a sintered metal porous strut. The air was compressed to 0.55 MPa by a screw compressor and then flowed into a buffer gas tank. The high pressure air was then dried and cooled by a refrigerated air dryer. The main flow was heated by an electric heater to the designated temperature and then flowed through the rectifier and the contraction section. A Laval nozzle was used to accelerate the air to supersonic flow. The coolant was room temperature dry air that bypassed the electric heater. Solenoid valves were used to adjust the mass flow rate of the main flow and the coolant. The mainstream total temperature was 398.15 K, the total pressure was 0.48 MPa and the Mach number was 2.8. An IR camera was used to measure the temperature distributions. A Schlieren system used to observe the shock wave distributions in the main flow field.

### 2.2. Porous struts

Struts are used to inject fuel into the core region of scramjet chambers for better combustion. Fig. 2 shows the half section and cross sectional views of the three strut structures investigated in this study. The struts were 36 mm long and 6 mm thick. The struts were 20 mm height and the strut leading edge had a 1.2 mm radius. A 4 mm thick porous rib was sintered in the internal cavity to enhance the strength. The two separated cavities were then connected to independent coolant pipes with different coolant mass flow rates for coolant usage optimization. The strut leading edge experienced the maximum thermal load due to the aerodynamic heating. Different leading edge structures were investigated as shown in Fig. 2. Strut A was the original structure of the strut leading edge with only transpiration cooling to protect the leading edge. The structure of strut A was modified to strut B by wire cutting a 0.20 mm width micro groove on the leading edge