



Transpiration cooling for additive manufactured porous plates with partition walls

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ABSTRACT

Transpiration cooling is an effective method to protect high heat flux surfaces such as rocket combustion chambers. However, this technology is currently not applicable for turbine airfoils as the strength of traditional sintered porous material was too low and the pore structure was uncontrollable. Consequently, developing porous media with high mechanical strength and precise geometry is important for transpiration cooling. Present study utilized the Selective Laser Melting Additive manufacturing technology to fabricate metal porous plates for transpiration cooling. Reinforcing partition walls were applied to the porous plate to further enhance the mechanical strength. Both cooling efficiency and mechanical properties were evaluated for the additive manufactured porous plates and compared to the traditionally sintered porous plate. The experimental results showed that the transpiration cooling efficiencies of the additive manufactured porous plates with partition walls approached to that of sintered porous plate, which approached to 0.7 when coolant blowing ratio was 2%. The presence of solid partition walls did not affect the cooling efficiency even for a high blocking ratio of 60%. The mechanical property was significantly improved by additive manufactured porous plate with partition walls. The ultimate tensile strength (UTS) increased by 440% compared to sintered porous material. Such results demonstrated that additive manufacturing and reinforced partition walls might be potential solutions to enhance the mechanical strength of transpiration cooling.

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1. Introduction

Thermal protection is important for hot section components of many equipment related to power generation or jet propulsion, such as gas turbine engines and spaceflights, which generally suffers from high temperature and high heat flux gas flows. Advanced gas turbine engines typically have a turbine inlet temperature well beyond the melting temperature of conventional materials to maintain a high cycle efficiency. Thus, effective cooling technologies are essential to increase the durability of high heat temperature components in gas turbines [1–4]. Conditions are even harsher in the field of spaceflight, where the maximum temperature of the combustion chamber of liquid-fueled rocket reaches 3600 K [5] and the aerodynamic heating on the leading edge of hypersonic vehicle reaches 1000 MW/m² [6]. Effective cooling

method is necessary to prevent ablation on these high heat flux walls.

Among numerous cooling technologies, transpiration cooling was considered as one of the most effective active cooling method to reduce the temperature of high heat flux surfaces. The transpiration coolant flowed through the permeable porous wall and then formed a film layer covered on the surface to reduce the heat transfer from the hot mainstream. The heat exchange between the coolant flow and porous solid matrix was intense because of the huge specific surface area and twisted micro tunnels in the porous media. Typical porous materials used for transpiration cooling include sintered metal porous material [7–10], porous ceramic [11,12], Ceramic Matrix Composite [13–15], platelet structure [16,17] and sintered woven wire structure [18].

Significant effort has been devoted into transpiration cooling in the past few decades, for multiple applications like gas turbine blades [12,19], rocket combustion chambers [20], leading edges [11,21] and scramjet fuel injectors [22]. Jiang et al. [9] and Huang et al. [23,24] investigated combined transpiration cooling methods for sintered stainless steel porous struts. Their experiments results

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Nomenclature

BR	the blockage ratio of the partition wall
P	pressure [Pa]
F	coolant blowing ratio
T	temperature [K]
X	dimensionless position
x	distance from the leading edge [m]
L	length of the porous plate [m]
UTS	ultimate tensile strength [GPa]
V	velocity [m/s]

Greek symbols

δ_1	width of the partition wall [mm]
δ_2	interval between two nearby partition wall [mm]
η	transpiration cooling efficiency [mm]
ρ	density [kg/m ³]

Subscripts

c	coolant
m	mainstream flow
w	porous wall

showed that the temperature distributions on the porous strut surface were uniform by adjusting the coolant distributions. Wang et al. [7] tested the transpiration cooling performance of a porous nose cone made of sintered alloy porous media in a heated gas wind tunnel. Their results showed that the unequal wall thickness was an effective way to increase the cooling efficiency in the stagnation point region. Forrest et al. [11] used Al_2O_3 and SiO_2 to manufacture three porous nosecones. Liquid water was applied to cool the heated porous nosecones and the results showed that the transpiration cooling efficiency was much higher than that using gas as coolant. Langener [13] investigated transpiration cooling for C/C porous plates using gaseous air, argon, and helium as the coolant. The cooling efficiency using helium as coolant was higher than other coolant because of higher specific heat capacity. The performance of transpiration cooling with sintered woven wire mesh structures were experimentally investigated by Xu et al. [18]. Their results showed that the cooling efficiency of transpiration cooling was higher than film cooling at certain conditions. However, the pore structure was uncontrollable and the strength of traditional sintered porous material was too low [25]. The strength significantly decreased with increasing the porosity of porous material [26]. Thus, transpiration cooling is currently not widely applied to cool the turbine airfoils which had a high requirement to the mechanical properties.

Additive manufacturing is an emerging advanced material incremental manufacturing technology, which is also called 3D printing method. Compared to traditional subtractive manufacturing methods, additive manufacturing has advantages in material consumption, economical cost, time efficiency and geometry complexity [27–29]. Common metal additive manufacturing methods include Selective laser sintering (SLS), Selective laser melting (SLM), laser metal deposition (LMD) and electron beam melting (EBM) [29,30]. Additive manufacturing was widely applied to biomedicine [31,32], aerospace [33], automotive [34], gas turbines [35,36] and so on. Previous studies have shown that additive manufacturing is an effective method to economically and efficiently manufacture complex geometry components with considerable mechanical properties [37]. Compared to the traditional machining methods, additive manufacturing could more efficiently and flexibly manufacture porous components with complex geometries and micro channels used for transpiration cooling.

Although additive manufacturing has shown extensive capability of making complex cooling structures, very few studies have considered implementing this novel technology in transpiration cooling and the associated impacts were not clear. The blades of the gas turbine are in a very harsh environment and experience risks of many kinds of damages, such as mechanical damage and high temperature damage [38]. The material strength and cooling efficiency for the cooling structure of the blade are both very important and should be both taken into account in practical

application. However, current studies of transpiration cooling mainly focused on the cooling efficiency but ignored the mechanical strength. Thus, improving the strength of porous material for transpiration cooling is necessary. The partition walls are equivalent to the reinforcing ribs, which are considered to be able to improve the material strength. There is little literature investigated the partition walls design for the porous material of transpiration cooling. The influences of partition walls on transpiration cooling efficiency and mechanical properties are not clear. In this study, a series of metal porous plates with precisely designed straight holes and partition walls were manufactured using the Selective Laser Melting (SLM) method. The SLM method has advantages to manufacture metal components with high precision and high strength. Conventional sintered porous plates were used as the control group. Multi-disciplinary characterization were conducted to evaluate the transpiration cooling efficiency and the mechanical properties of the additive manufactured porous plates. The mechanism of the transpiration flow through the additive manufactured porous plates was further analyzed using numerical method. Particular interest of present study was in the effect of partition wall and the impact of additive manufacturing on transpiration cooling.

2. Experiment investigation

2.1. Test facility

Fig. 1 shows the experimental system for investigating the transpiration cooling for the porous plates. The air was heated by the electric heater and then flowed through a cellular rectifier. The cross section of the mainstream channel in the test section was rectangular with a size of 200 mm × 200 mm. Compressed air fed from a high pressure air source up to 0.6 MPa and 296 K was used as the transpiration coolant to cool the porous plates. Two K type thermocouples were installed in the test rig to measure the mainstream temperature and the coolant temperature. The mainstream velocity was measured by a pitot tube and a digital manometer.

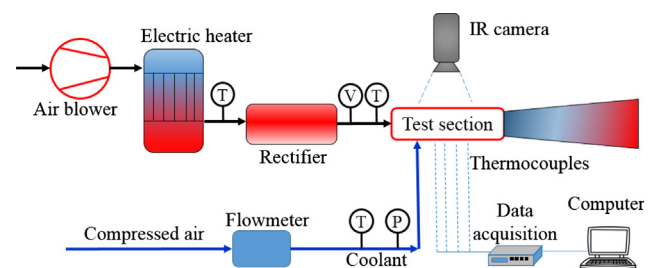


Fig. 1. Experiment system.

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