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Experimental study of multi-hole cooling for integrally-woven, ceramic matrix composite walls for gas turbine applications

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ABSTRACT

In this paper, multi-hole cooling is studied for an oxide/oxide ceramic specimen with normal injection holes and for a SiC/SiC ceramic specimen with oblique injection holes. A special purpose heat transfer tunnel was designed and built, which can provide a wide range of Reynolds numbers ($10^5 \sim 10^7$) and a large temperature ratio of the primary flow to the coolant (up to 2.5). Cooling effectiveness determined by the measured surface temperature for the two types of ceramic specimens is investigated. It is found that the multi-hole cooling system for both specimens has a high cooling efficiency and it is higher for the SiC/SiC specimen than for the oxide/oxide specimen. Effects on the cooling effectiveness of parameters including blowing ratio, Reynolds number and temperature ratio, are studied. In addition, profiles of the mean velocity and temperature above the cooling surface are measured to provide further understanding of the cooling process. Duplication of the key parameters for multi-hole cooling, for a representative combustor flow condition (without radiation effects), is achieved with parameter scaling and the results show the high efficiency of multi-hole cooling for the oblique hole, SiC/SiC specimen.

1. Introduction

New integrally-woven, ceramic matrix composites (CMC) formed by the 3-dimensional weaving of fibers, which can be multi-hole cooled, offer the prospect of substantial combustion system gain and they are being developed for gas turbine applications. The aim is to reduce the coolant gas requirement for combustor liner cooling, as well as to increase the combustor inlet temperature. Cox et al. [1] and Mehta et al. [2] discuss potential applications of integrally-woven CMC materials for gas turbine combustor liners. With the development of weaving and processing techniques, a relatively large number of small holes through the CMC material can be easily provided with minimal cost penalty and, at the same time, the mechanical and thermal strength can be maintained. As an example, Fig. 1 is a photograph of the multi-holed surface of an all-oxide ceramic specimen.

A multi-hole cooling system (also called "effusion cooling"), which has a relatively large number of injection holes of small size[1], introduces a secondary cold flow into the primary hot flow through these holes as shown schematically in Fig. 2. The coolant is then carried downstream by the primary flow. With an optimal design of the cooling configuration and at a specific operating condition (Reynolds number of the system, blowing ratio, temperature ratio), most of the coolant will flow near the target surface so that a stable cool film can be formed over the surface, which separates the surface from the high temperature and large heat flux in the primary flow. Compared to traditional 3D film cooling with a few relatively large holes, a multi-hole cooling system is expected to have a higher cooling efficiency[2] and be able to achieve a more uniform surface temperature distribution because of its relatively large percentage of hole area (>1%) produced by a large number of small holes. To the authors' knowledge, little is known about the fluid mechanics and heat transfer in the application of such multi-hole cooled CMC systems. Zhong & Brown [3] studied multi-hole cooling for an oxide/oxide specimen and provided some preliminary results for the cooling effectiveness. Subsequently, the experimental facility was fully insulated and modified to enable a temperature ratio between free stream and coolant of up to 2.5 to be obtained. The present results greatly extend and supersede this early work and also include results for the SiC/SiC material with a different hole geometry and thermal properties.

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[1] The typical hole size for a multi-hole cooling system, which would have acceptable clogging behavior in gas turbine applications, is in the range of 0.5∼1 mm, while the hole size for a typical 3D film cooling application is generally larger. For cooling applications with boundary layer flows, a multi-hole cooling system may have a ratio of hole length/width to boundary layer thickness in the range of 0.1 or less, whereas, film cooling has a hole size comparable to the local boundary layer thickness or larger.

[2] Compared with conventional film cooling for typical applications, which has a blowing ratio of approximately $M \sim 1$ to 2 or higher, the multi-hole cooling systems in these experiments have a significantly lower blowing ratio ($M \sim 0.8$) for a comparable cooling effectiveness.

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Nomenclature

A	area
d	wall thickness
L	streamwise distance from the entrance to the $4'' \times 4''$ square test section of the tunnel to the leading edge of the cooling specimen (approximately 0.34 m)
I	momentum ratio defined as $\frac{(\rho v^2)_c}{(\rho u^2)_\infty}$
k	thermal conductivity
M	blowing ratio defined as: $\frac{(\rho v)_c}{(\rho u)_\infty}$
N	total mass flow rate ratio
P	pressure
P_{h}	hole to hole spanwise distance
Re	Reynolds number defined by the streamwise distance L and free stream velocity
S_{h}	hole to hole streamwise distance
T	temperature
t	time
Tu	turbulence level
uvw	velocity components
xyz	streamwise, normal, spanwise direction

Greek symbols

θ	cooling effectiveness defined as $\theta = \frac{T_{w_{\text{no-cooling}}} - T_{w_{\text{with-cooling}}}}{T_{w_{\text{no-cooling}}} - T_c}$
α	hole angle
ρ	density
δ	boundary layer thickness
η	non-dimensional temperature
β	percentage of the hole area
κ	temperature ratio defined as $\frac{T_\infty}{T_c}$
μ	dynamic viscosity
v	coolant mean injection velocity

Subscripts & superscripts

c	coolant
h	hole
w	wall
∞	free stream

Importantly, a multi-hole cooling system can provide a substantial backside cooling effect due to the heat convection to the backside coolant flow and the heat conduction through the wall. Thin wall, integrally-woven, CMC materials are, in fact, relatively conducting. (Compared with super-alloy walls with a thermal conductivity of approximately 100 W/m/K, CMC materials have a smaller thermal conductivity of 4~15 W/m/K, but this value is still relatively large compared with many ceramics $k < 1$ W/m/K.) In their recent detailed numerical study, Zhong and Brown [4] addressed the importance of the backside cooling effect for a multi-hole oxide/oxide specimen and proposed a 3D coupled heat transfer model, which includes all heat transfer processes (except radiative heat transfer) in a multi-hole cooling system. Their DNS solutions show the significant effect of the backside cooling and their predictions of the cooling effectiveness agree well with the experimental results at the same Reynolds numbers and cooling conditions.

In this paper, multi-hole cooling is studied experimentally with a special purpose heat transfer tunnel. Two types of woven CMC materials have been investigated and the effects of blowing ratio, temperature ratio, Reynolds number, hole geometry and the thermal properties of the wall material are explored. Another objective of this study was to duplicate the cooling process for representative combustor flow conditions (in the absence of radiation effects) through parameter scaling but using the same material and geometry. For example, if we assume a maximum combustor main-stream temperature of approximately $T_\infty \sim 2400$ K[3], $T_c \sim 1000$ K for the coolant temperature, $U_\infty \sim 60$ m/s for the main-stream velocity and $P_\infty \sim 60$ atm for the static pressure, the heat transfer tunnel can be operated at values of temperature and pressure that are 1/6 of these values, i.e. at a tunnel temperature of 400 K, a coolant temperature of 167 K and a tunnel pressure of 10 atm. This scaling enables the density[4] and density ratio (ratio of coolant to main-stream) to be the same as for an actual combustor flow. By using the same CMC material and geometry as in the actual combustor liner, the same Reynolds number (based on the characteristic dimension for the geometry of the liner material) can be obtained by adjusting the free stream velocity as follows.

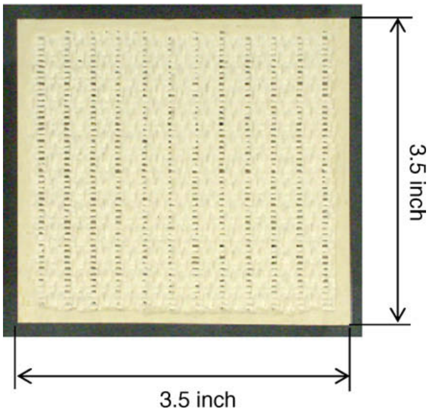

Fig. 1. Multi-holed surface of the oxide/oxide specimen.

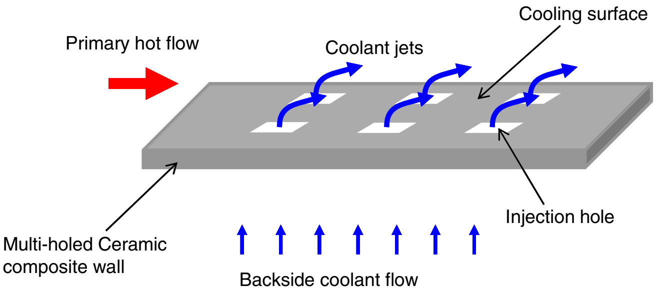

Fig. 2. Schematic diagram of a multi-hole cooling system.

With $\rho_{\text{real}} = \rho_{\text{test}}$, $d_{\text{real}} = d_{\text{test}}$ and assuming that $\frac{\mu_{\text{test}}}{\mu_{\text{real}}} \sim \left(\frac{T_{\text{test}}}{T_{\text{real}}}\right)^{0.667}$, the same Reynolds number requires:

$$\frac{U_{\text{test}}}{U_{\text{real}}} = \left(\frac{T_{\text{test}}}{T_{\text{real}}}\right)^{0.667} \tag{1}$$

In this example, we have $U_{\text{test}} = 60\left(\frac{1}{6}\right)^{0.667} = 18\text{m/s}$.

Thus for the same density ratio, and hole velocity to freestream velocity ratio, and the same Reynolds number based on hole size (same liner geometry) we would also require the same d/L or d/δ. Of course L or δwill vary with the application but the present scaling ensures a matching of the principal parameters, velocity ratio,

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[3] The flow conditions used here are obtained with reference to proposed working conditions for a future turbine engine combustor, for example, a 2-D Trapped Vortex Combustor.

[4] The same density is based on the assumption of a perfect gas.