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A convolution modeling method for pore plugging impact on transpiration cooling configurations perforated by straight holes

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ABSTRACT

Transpiration cooling is one of the most efficient cooling technologies to protect hot section components such as turbine airfoils, missile heads and shells of rockets or space craft. This external cooling method has much higher efficiency than film cooling when consuming the same amount of coolant, due to the uniformity of coolant distribution. However, pore plugging, which frequently occurs during the operation of transpiration cooled components, has limited its long term stability and prevented its application in industrial components. Dust deposition is one of the main reasons causing plugging of pores for transpiration cooling. Although a lot of effort has been devoted into explaining dust deposition and erosion mechanisms of transpiration cooled components, reducing plugging impact remained difficult as the plugging caused by dusts was unpredictable for traditional porous media. Additive manufacturing, with capability to precisely construct structures in small scales, has emerged as considerable new tool to enhance the controllability of porous media, and furthermore, to achieve a good solution to minimize the plugging disadvantage. The present study selected a transpiration cooling configuration perforated by straight holes with an additive manufacturable diameter of 0.4 mm. Computational Fluid Dynamics (CFD) methods were employed to model the pore plugging and its effect on heat transfer. A scripting code in addition to the ANSYS CFX solver was utilized to simulate the random plugging conditions of the holes. Two hundred numerical cases with four different plugging probabilities were calculated and statistically evaluated to quantify the disadvantage of pore plugging on the cooling effectiveness. A theoretic model with convolution functions was developed to predict the local cooling effectiveness. Results obtained from the numerical analysis indicated that the overall plugging ratio was a dominating parameter for the cooling effectiveness but this single parameter was not adequate to scale the cooling effectiveness for all locations. On the contrary, the unique pair of discrete convolution parameters indexing all other transpiration holes in the array developed in this study had a significantly higher accuracy in predicting the cooling effectiveness than the overall plugging ratio. The present study was among one of the earliest to use convolution modeling method to predict transpiration cooling and related plugging disadvantages. This effort could provide a quantitative understanding of the random plugging on the specific transpiration cooling configuration, and could benefit further optimization effort to reduce the plugging disadvantage of transpiration cooling using additive manufacturing.

1. Introduction

Transpiration Cooling is an effective cooling technology to protect hot section components such as gas turbine airfoils [1], rocket heads and space craft [2–4]. Through intensive micro pores, coolant ejects uniformly into the hot gas path and forms a thin cold film to protect the hot surface. Meantime, the coolant flow through the micro pores also provides significant internal cooling to the metal/ceramic matrix. Due to the global integration of internal and external cooling, transpiration cooling has much higher efficiency than film cooling with shaped holes which typically focuses on a local region when consuming the same amount of coolant.

Numerous investigation has been conducted in heat transfer properties of transpiration cooling in the past few decades. Forrest et al. [5] used liquid water as the coolant in porous nosecones for transpiration cooling. Results obtained from the liquid experiments showed a much higher cooling effectiveness compared to air coolant. Langener et al. [6] developed a model to predict transpiration cooling efficiency for porous C/C walls based on previous

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Nomenclature

A_c	cooled target surface area [m^2]
Bi	Biot number, $Bi = k_sL/h_{g0}$
D	hole diameter [m]
F	injection ratio, $F = m_c/\rho A_c$
f	streamwise weight function for convolution
g	spanwise weight function for convolution
H	channel height [m]
h_{g0}	external heat transfer estimated by the Dittus-Boelter Correlation
i	relative hole number in streamwise direction
j	relative hole number in spanwise direction
k_s	thermal conductivity of the solid material [W/m·K]
L	thickness of the porous plate [m]
m_c	coolant mass flow rate [kg/s]
ni	number of columns of holes
nj	number of rows of holes
P_x	streamwise pitch between holes [m]
P_y	spanwise pitch between holes [m]
T_c	coolant inlet temperature [K]
T_g	mainstream inlet temperature [K]
T_s	external surface temperature of the metal part [K]
T^*	non-dimensional temperature
Re	mainstream Reynolds number, $Re = \rho U_g H/\mu$
U_g	mainstream flow velocity [m/s]
x	streamwise coordinate [m]
y	spanwise coordinate [m]
y^+	non-dimensional thickness of the first layer of meshes

Greek symbols

β	plugging ratio of the entire porous plate
η	cooling effectiveness
η_{ave}	averaged cooling effectiveness across the outer surface of the porous plate
γ	plugging probability
ξ	convolution variable
ε	logic value representing plugging condition of a single hole
ρ_c	density of coolant air [kg/m^3]
ρ_g	density of hot gas [kg/m^3]
μ	dynamic viscosity of fluid [Pa·s]
σi	standard deviation of streamwise weight function
σj	standard deviation of spanwise weight function

results. Cooling experiments were conducted using different kinds of coolant to build up the model and non-adiabatic test environments were taken into account for the prediction. Wang et al. [7] applied transpiration cooling to a nose cone of hypersonic flights. Effort focused on minimizing the coolant flow rate using unequal wall thickness while keeping the average cooling effectiveness at a relative high level. Huang et al. [8] investigated a combined transpiration cooling using opposing jet cooling for struts, which allowed adjusting of flow rate between the two types of geometries. Uniform temperature distribution on the strut surface was achieved using the optimal coolant distribution.

Although previous results already indicated high potential of transpiration cooling, which could significantly elevate the cooling efficiency for turbine components from the current level provided by film cooling [9], significant challenge still remains in the gap between porous media and turbines. Pore plugging, which frequently occurs during the operation of turbine components, has prevented the application of transpiration cooling in gas turbines components which required long term stability. Dust deposition is one the main reasons causing plugging of pores for turbine components. For transpiration cooling, the dusts have a wide range of diameters and the induced plugging can be partial or complete for each pore. Additionally, the location of plugging is generally random and unpredictable due to the limited information of pores, (e.g. pore size, pore geometry and pore locations) which makes transpiration cooling more impractical. Yu et al. [10] developed a physics based model to predict the impact and deposition of sand particles. Results showed that both particle size and temperature had an effect on the deposition characteristics. Steven et al. [11] investigated the effect of the external metal temperature on flow blockage development in a simplified vane leading edge with impingement. The strongest influence on flow blockage development was found in and around the impingement holes.

One important reason for the low controllability of transpiration cooling, such as the low anti-plugging property described above, is due to the manufacturing technologies. Typical transpiration cooling structures are manufactured by foundry, powder metallurgy, sintering, lamination or ceramic matrix compositing [6,12–14]. These manufacturing technologies have limited capability to construct precise mini/micro features for porous media and consequently resulted in the low controllability to plugging. In contrast to these conventional manufacturing technologies, additive manufacturing [15–17], which was maturing in recent years, can provide substantial capability to build mini/micro scale structures precisely. Among these technologies, selective laser melting technology is the most widely used and can provide a geometry precision of 0.1 mm for Nickle based alloys, which can be used in turbine components. However, additive manufacturing also has risks of blocking pores due to occasional powder sintering and roughness inside the pores. As a consequence, substantial effort needs to be devoted into designing and optimization of precise and complex porous media to properly take advantages of additive manufacturing.

With the advantages described above for additive manufacturing, research could be conducted through multiple avenues to control the impact of plugging on transpiration cooling. One immediate idea was to fabricate transpiration cooling pores into regular micro holes or micro channels with prescribed shapes. Diameters could be optimized and set at an appropriate value, which could reduce the probability of plugging induced by dusts to an acceptable extend while maintaining sufficient cooling efficiency when plugging actually occurred. As an initial and necessary step of this approach, designing tools for additive manufacturable porous media needs to be developed and visible understanding of the random plugging disadvantage on transpiration cooling should be obtained. This effort utilized Computational Fluid Dynamics (CFD) to simulate the dust plugging effect on a perforated plate which was additive manufacturable. Random plugging was assigned to each hole by a scripting code and statistical analysis were performed on the basis of a considerable quantity of thermal fluid results. A theoretic model with convolution functions was developed to predict the local cooling effectiveness. This effort was expected to contribute to the knowledge base of plugging effect and benefit further optimization using additive manufacturing.

2. Methodology and setup

2.1. Geometries, computational domain and boundary conditions

The present study selected a porous metal plate with multiple rows of straight holes as the simulation object. The selected porous