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Study on analogy principle of overall cooling effectiveness for composite cooling structures with impingement and effusion

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ABSTRACT

The overall cooling effectiveness, which represents the distribution of dimensionless temperature on gas turbines surface, is an important parameter for conjugate heat transfer analysis of gas turbines. Generally, it is difficult to measure the overall cooling effectiveness in engine condition. However, the overall cooling effectiveness can be measured in the laboratory by matching the appropriate parameters to those in engine condition. Thus, it is important to evaluate the key parameters of matching methods. In this paper, the effects of adiabatic film effectiveness and Biot number on the overall cooling effectiveness were investigated with an impingement/effusion model by numerical simulation, in which 3-D steady RANS approached with the k–ω SST turbulence model was used. The tested plate had 8 cylinder hole rows with 30 degree inclined angle, and the internal cooling employed staggered array jet impingements. The matching performance was evaluated by comparing the results in typical engine condition and laboratory condition. The analogy principles were discussed in detail. The results show that the overall cooling effectiveness can be matched by using suitable matching principle in different lab conditions. The theoretical analysis was verified by numerical results. The distributions and values of overall cooling effectiveness can be matched well between engine condition and lab condition by matching temperature ratio, mainstream side Biot number and blowing ratio. If the temperature ratio is mismatched, the momentum flux ratio will be an important parameter for overall cooling effectiveness, because matching momentum flux ratio can reduce the difference of the adiabatic cooling effectiveness and the heat transfer coefficient ratio between engine condition and laboratory condition.

1. Introduction

The development of high performance gas turbine engines is accompanied by the ever-increasing thrust. Increasing the turbine inlet temperature becomes an important way to meet the ever-increasing thrust demand. With the increase of turbine inlet temperature, a variety of cooling methods are used to ensure reliable operation of turbine. The external film cooling and internal cooling channel play very important roles in gas turbine cooling system.

The film cooling characteristic is usually evaluated by both the adiabatic cooling effectiveness (η) and heat transfer coefficient ratio (h_g/h_0). However, the temperature on gas turbine surface depends on conjugated effect, which including external cooling, internal cooling and conduction. The actual temperature on the turbine surface determines whether the hot components can work reliably or not. The ideal method of studying the conjugated heat transfer of turbine hot components is to measure the data in actual engine condition. However, this is obviously difficult because of the limitation of measurements. Thus, it is important to find reliable research methods in laboratory condition.

There are many previous studies about conjugate heat transfer in laboratory. Martiny et al. [1] found that mainstream side Biot number $\left(Bi_g = \frac{h_g \delta}{k}\right)$ has a significant impact on conjugate heat transfer in effusion-cooled model. An infrared technique was used to measure the overall cooling effectiveness (ϕ) by Sweeney et al. [2], who chose 6–4 titanium as the film plate material to achieve the similar Biot number (Bi_g) between the laboratory and the engine. They obtained the overall cooling effectiveness under different parameters. The overall cooling effectiveness is a non-dimensional parameter, which represents the actual surface temperature in conjugate heat transfer model. The overall cooling effectiveness is defined as:

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Nomenclature

D	diameter of film hole, [m]
h	heat transfer coefficient, [W/m^2 K]
M	blowing ratio, [$=\rho_c U_c/\rho_g U_g$]
I	momentum flux ratio, [$=\rho_c U_c^2/\rho_g U_g^2$]
T	temperature, [K]
P	pressure, [Pa]
S	source term
k	thermal conductivity, [W/mK]
Re	Reynolds number, [$=\rho u D/\mu$]
Pr	Prandtl number
Bi	Biot number, [$Bi_g = h\delta/k$]
u	velocity, [m/s]
X	coordinate axis of the mainstream direction, [m]
Y	coordinate axis of the lateral direction, [m]
Z	coordinate axis of the height flow direction, [m]
l	characteristic length
H	enthalpy
t	time
m	mass flow rate, [kg/s]

Greek symbols

η	adiabatic cooling effectiveness
ϕ	overall cooling effectiveness
ρ	density, [kg/m^3]
μ	dynamic viscosity, [Pa · s]
δ	thickness of film plate
τ	rate of strain tensor
χ	warming factor, [$= (T_g - T_{c,e})/(T_g - T_{c,i})$]
Θ	non-dimensional temperature, [$= (T_g - T)/(T_g - T_{c,i})$]

Subscripts

0	without film cooling
1	typical engine condition
2	laboratory condition
aw	adiabatic wall
w	conjugate wall
w,s	conjugate wall in solid side
w,flow	conjugate wall in flow side
c	coolant side
c,i	coolant at inlet
c,e	coolant at exit
g	mainstream side
s	solid of film plate

$$\phi = \frac{T_g - T_w}{T_g - T_{c,i}} \quad (1)$$

where T_g, $T_{c,i}$, T_w are the mainstream temperature, coolant temperature at the inlet and local wall temperature in conjugate heat transfer condition, respectively. The overall cooling effectiveness, which can be measured in lab condition, can be used to predict the temperature distributions of actual turbine components by proper methods. Albert et al. [3] presented an analogy principle with a brief one-dimensional analysis on an airfoil wall. The analogy analysis indicated that the overall cooling effectiveness can be matched in laboratory condition by matching the mainstream side Biot number and heat transfer coefficient ratio h_g/h_c. Further theoretical development by Albert et al. [4] showed that the adiabatic cooling effectiveness (η) is another important parameter in analogy principles. The correlation of these parameters can be described as follows:

$$\phi = \frac{1-\eta}{1 + Bi_g + h_g/h_c} + \eta \quad (2)$$

Based on the analogy principles, Albert et al. [4] also studied the performance of trench hole on turbine vane pressure side. Dyson et al. [5] measured the overall effectiveness on a turbine blade leading edge with different film hole pitch and flow parameters.

Nathan et al. [6] further expanded the analogy theory, they obtained these analogy parameters by using three dimensional approach. The improved correlation of these parameters can be expressed as follows:

$$\phi = \frac{1-\chi\eta}{1 + Bi_g + h_g/h_c} + \chi\eta \quad (3)$$

The new analogy parameter is warming factor $\left(\chi = \frac{T_g - T_{c,e}}{T_g - T_{c,i}}\right)$, which accounts for the increasing of coolant temperature as it passes through the internal cavities of the model. Nathan et al. [6] measured the adiabatic effectiveness and overall cooling effectiveness on a scaled turbine vane leading edge with an internal impingement cooling configuration. The results showed that the cooling performance was continuous enhanced with the increase of momentum flux ratio. Williams et al. [7] used the same turbine vane model to measure the adiabatic and overall effectiveness on suction side. Based on one-dimensional thermal analysis, Williams et al. [7] tried to predict the overall cooling effectiveness by using the adiabatic film effectiveness and overall cooling effectiveness without film cooling. Above research [4–7] studied the conjugate heat transfer only on simplified turbine vane model. Chavez et al. [8,9] studied the overall cooling effectiveness on a turbine vane with realistic internal cooling and film cooling configurations. In order to match the mainstream side Biot number to those of the actual turbine blade, they used DuPont™ Corian® as the turbine vane material, which was verified through CFD and earlier experimental work, to match mainstream side Biot number. The experiment results showed that internal cooling play an important role in the overall cooling effectiveness, and they measured the values of warming factor.

Based on energy equilibrium, the analogy analysis of conjugate heat transfer model was studied by Li et al. [10]. They also found that the overall cooling effectiveness was correlated with mainstream side Biot number, adiabatic cooling effectiveness, heat transfer coefficient ratio and the warming factor. Li et al. [10] investigated the parameters influence on the overall cooling effectiveness by differentiating the correlation equation of overall cooling effectiveness. The values of partial derivatives showed that the overall cooling effectiveness is most sensitive to the change of adiabatic, and robust with the change of warming factor.

The cooling configurations of actual turbine usually contain complicated internal cooling, and there are many conjugate heat transfer research on plate with complicate internal cooling. Dees et al. [11,12] researched the conjugate heat transfer effects on an internally cooled vane by using both experiment and numerical simulation. They used the castable epoxy to match mainstream side Biot number to that in generic engine condition. The results showed that the overall cooling effectiveness mainly depends on the internal and external heat transfer intensity. Mensch and Thole et al. [13,14] measured the overall cooling effectiveness on a blade endwall by approximately matching mainstream side Biot number. The respective and combined cooling effectiveness of external film cooling and internal jet impingement cooling were tested. The