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Investigation on film cooling with swirling coolant flow by optimizing the inflow chamber

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ABSTRACT

Three different kinds of coolant chamber configuration for film cooling are proposed to develop the swirling coolant flow at blowing ratios ranging from 0.5 to 2.0. The results show that the difference of film cooling effectiveness for three kinds of coolant chamber configuration is little at low blowing ratio, but the advantage of swirling film cooling becomes obviously with the increase of blowing ratio. When the blowing ratio is 2.0, the jet momentum of original coolant chamber configuration is large and uniform, which leads to the lowest cooling effectiveness due to the formation of a strong kidney vortex. The first coolant chamber configuration has a low jet momentum region at upstream of the film hole, the coolant in this region interacts with high temperature mainstream and bypasses the large jet momentum coolant to attach cooling surface at downstream. The second coolant chamber configuration is sprayed with the structure of unidirectional vortex, which forms a vortex pressing on other vortex, making the coolant in pressed vortex attach surface better, producing the best coverage and the higher film cooling effectiveness.

1. Introduction

For modern gas turbine engine, the inlet temperature of the high pressure turbine (HPT) stage has far exceeded the endurance of the materials, the advanced cooling technology is widely used to solve this problem, and film cooling is one of the key cooling methods [1]. Film cooling method use the coolant air which is injected from dispersed cooling holes is to extract the corresponding compressor stage cooling gas from one or more discrete holes in the jet, on the high-temperature wall surface to form a gas film to block the wall is not the mainstream of high temperature gas ablation [2].

Goldstein et al. [3] first studied the effect of the blowing ratio on the cooling effectiveness of the cylindrical film hole, it was found that the optimum blowing ratio was around 0.5. Leylek et al. [4] found that when the blowing ratio equals to 2.0, a typical kidney-shaped vortex pair presented downstream of the cylindrical holes, and two important aerodynamic characteristics occurred. The first one was that the vortex pair had stronger vortex core and lifted the coolant injection off the wall, and the other one was that the high temperature freestream was sucked into the bottom region of the coolant injection from neighbor, resulting in poor cooling effectiveness. The cylindrical film hole could not have effective coverage with high blowing ratio because that the coolant injection would not be attached on the wall and finally decreased the cooling effectiveness [5]. In order to solve this problem, new type of the film cooling hole and high effectiveness cooling emission method have become one of the open issues. Zhu et al. [6] studied the film cooling effectiveness of the cylindrical hole, taper holes, dustpan-shaped holes and shrink-expanded holes by experimental and numerical methods, it was found that the modified shape cooling holes had higher cooling effectiveness than that of the cylindrical hole. Dai et al. [7] further studied the cooling effectiveness of the crescent hole. Okita et al. [8] investigated the effectiveness of arrow-shaped holes. Dai et al. [9] increased the film cooling effectiveness by adding vertical slot at the exit of the cooling hole. Kusterer et al. [10–11] first proposed the two-injection structure which combined two cylindrically-shaped holes together, this new shape cooling holes could generate an anti-kidney vortex pair which had reverse rotation direction of the kidney-shaped vortex. Marc et al. [12] also proposed a new type of sister cooling holes. However, the new shape holes which were discussed above still had many difficulties in the processing technology, structural strength design and working condition matching, and the most popular application was the cylindrical hole. Takeishi and Oda [13–15] studied the film cooling effectiveness of circular and fan-shaped film cooling holes with a swirling film coolant injected through a flat plate and the endwall of a high-loaded first nozzle by experimental and numerical methods, the results showed that film cooling with swirling coolant flow led to

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Nomenclature

D	Diameter of the film cooling hole, m
M	Blowing ratio, –
P	Hole spacing, m
T_{aw}	Adiabatic temperature, K
T_g	Temperature of freestream, K
T_c	Temperature of coolant air, K
v_c	Average inlet velocity of coolant, m/s
v_∞	Velocity of freestream, m/s
X	Streamwise coordinates, m
Y	Vertical coordinates, m
Z	Spanwise coordinates, m

Subscripts

α	Exit angle of film cooling hole, deg
η	The cooling effectiveness, –
ρ_c	Density of coolant air, kg/m^3
ρ_∞	Density of freestream, kg/m^3
y^+	Non-dimensional distance, –

drastic improvements in the film cooling effectiveness. This improvement was attained owing to enhanced interaction between the swirling film jet and the main stream. Furthermore, the swirling motion destroyed the anti-kidney vortex structure and helped to adhere the film cooling air on the wall.

In this work, the flow structure of the coolant in film hole is controlled by changing the way of the cooling air entering the film hole on the basis of the cylindrical film cooling hole. Two new shapes of coolant chamber are investigated compared to the original coolant chamber, the film cooling effectiveness with different cooling structures is studied.

2. Numerical model

2.1. Geometric configurations and physical model

The calculation domain and the three-dimensional structure of three shapes of coolant chamber are shown in Fig. 1 and Fig. 2. The shape of film hole is cylinder which has absolute advantage in processing technology and structural strength design. The diameter of the film cooling hole (D) is 8 mm, the center of film hole locates at the origin of the coordinate, the main flow direction is the positive X- axis, and the coolant flow direction is the positive Y-axis. The calculation domain is $10D \times 30D$, the height is $15D$, the hole spacing ratio(P/D) equals to 3, and the exit angle of film cooling hole(α) is 25°. As shown in Fig. 2, the first shape of coolant chamber (G1) changes the inlet direction of coolant air. The contact surface between the original coolant chamber and the film cooling hole is the positive Y surface, but the contact surface of the first shape coolant chamber is the positive X surface, the length of the coolant chamber is reduced by half in the X direction, whereas, the other parameters of the first shape coolant chamber remain unchanged. The second shape of coolant chamber (G2) is the further modification of the G1 model. The main purpose is to produce a one-way vortex in the film cooling hole, the calculation model of the second shape of coolant chamber is same as the G1 model.

2.2. Turbulence model

For the numerical calculations of heat transfer and cooling technology, the accuracy and reliability of the calculation results are directly affected by the selection of turbulence model. In this paper, the classical experiment conducted by Sinha et al. [16] is studied by numerical method, the prediction study is compared against the experimental data to verify the turbulence models. The boundary conditions and the computation model used in the simulation strictly follow the definition of the experiment. The predictions with different models are compared to the experimental data in Fig. 3. At the blowing ratio of 1.0, the prediction with the Shear-Stress-Transport (SST) model is in good agreement with the experimental data. The SST turbulence model has high prediction accuracy for film cooling effectiveness, the SST model is adopted as the selected turbulence model in this paper [17].

2.3. Boundary conditions and mesh generation

As shown in Fig. 1, the boundary conditions of the three kinds of coolant chamber include as follows: the high temperature free stream inlet, the coolant air inlet and pressure outlet. In the three kinds of coolant chamber, the two planes which are perpendicular to the Z-axis calculation models are set as periodic boundary condition, and other surfaces are set as non-slip adiabatic wall. The velocity and the temperature of the mainstream are set as constant in the inlet boundary condition. The inlet velocity (v_∞) is 20 m/s, the inlet temperature is 300 K. The inlet velocity of coolant air is determined by the blowing ratio, and the selected blowing ratios are 1.0, 1.5 and 2.0 in this paper, the temperature of film cooling air is kept constant at 150 K, and the pressure outlet is set at 1 atm.

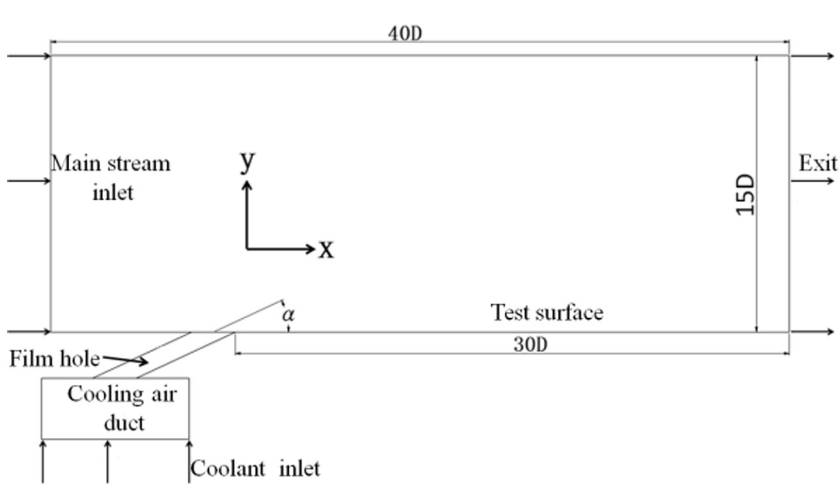

Fig. 1. Schematic of the computational domain.