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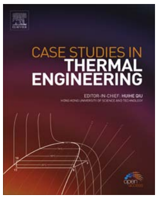

Film cooling modeling of a turbine vane with multiple configurations of holes

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ABSTRACT

Film cooling flow is important for gas turbine thermal protection. But it is difficult to predict the film cooling flow performances. The aim of this paper is to modeling the film cooling flow of a turbine vane with endwall film cooling, showerhead film cooling, and pressure/suction side film cooling simultaneously. Developing a method by adding endwall film cooling domain, the endwall film cooling flow can be simulated by CFD. This method can include heat transfer between flow and solid and capture the coolant details in the entering tubes. The conjugate heat transfer (CHT) method was utilized for fluid-solid thermal transfer at interfaces. The results show that the highest film overall effectiveness occurred immediately downstream the holes. The distribution of overall effectiveness is relatively homogenous in the zones between holes row in the leading edge no matter considering solid conduction. Without solid thermal transfer, better lateral coverage downstream the holes can form due to higher density ratio. The overall effectiveness and temperature field are affected by solid conduction, but the aerodynamic performance keeps consistent. Single row of holes in endwall cannot form good coverage in the lateral direction, but the showerhead film cooling configuration can form a preferable coverage layer.

1. Introduction

Film cooling technique is an important and effective thermal protective approach for advanced turbine blade and vane. Since 1970s, the application of film cooling plays a crucial role in gas turbine development. Today, film cooling holes are manufactured not only in the leading edge, pressure side, and suction side, but also in the endwall and blade tip. The full coverage configuration of film cooling is often used in several extreme environments.

For the profits of film cooling, plenty of papers focus on the heat transfer performances of the film cooling and the hole geometry shape and configurations [1–3]. Hylton et al. [4] carried film cooling flow experiment of a vane with the conditions ranges consistent with actual engine conditions. Their results show considerable cooling benefits of the downstream film cooling flow. The film cooling process was controlled by two competing mechanisms. One is the thermal dilution effects of the relative cold coolant that benefits decreasing of heat transfer, and the other is the turbulence that results in increasing of heat transfer induced by coolant injection process. It is suggested that conditions of coolant and mainstream, hole geometry and configuration, and airfoil geometry affect the performances of film cooling [5]. Baldauf et al. [6,7] measured the flat plate adiabatic film-cooling effectiveness by thermographic. They found that besides the cross-flow behavior of coolant ejected from discrete holes, these parameters blowing rate, density ratio, turbulence intensity, ejection angle, and hole spacing demonstrate the effect of adjacent jet interaction and impact on jet lift-off and

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adiabatic effectiveness. Nathan et al. [8] measured the adiabatic and overall effectiveness of showerhead film cooling of a turbine vane. Their results proved that the adiabatic film effectiveness improved continuously with increasing momentum flux ratio up to the maximum value of 6.7, although the coolant jets in the showerhead region were detaching from the surface for all momentum flux ratios larger than the value of 0.76. It concluded that adiabatic film effectiveness increased with momentum flux ratio in the showerhead region despite separation of the coolant jets.

For determining the film cooling heat transfer, the conventional method based on the adiabatic film cooling effectiveness and heat transfer conditions for test configurations. But additional influences of the interaction of fluid flow and heat transfer as well as influences of additional convective heat transfer cannot be taken into account accurately [3]. Results of the CHT method and the conventional method show that the magnitude of the peak secondary flow velocities of the adiabatic part can be as twice as the conjugate part [3]. These results confirm that the conjugate calculation can take into account the mutual influences of heat transfer on the fluid flow and vice versa. Thus, the conjugate heat transfer (CHT) method is used frequently to calculate heat transfer of film cooling [1,2,9–11]. Bohn and Krewinkel [12] modeled the fluid flow on a flat plate with full-coverage film cooling by CHT method and adiabatic calculations. They remarked that the conjugate calculation technique shows a deviation in the secondary flow compared to adiabatic calculations. Owing to the heat flux between the flow and the solid body, a more homogenous temperature distribution exists on wall.

The early published work on endwall film cooling is contributed by Blair [13]. He found that both heat transfer and film cooling on endwall are affected by secondary flow. Takeishi et al. [14] made experimental observation and revealed that the horseshoe vortex increased the heat transfer and decreased the film cooling. Friedrichs et al. [15] measured the film cooling effectiveness distribution on a endwall. They found interaction of the coolant ejection and secondary flow. The secondary flow influenced the trajectory of coolant flow, and the coolant ejection delayed separation of the inlet boundary layer on endwall. The endwall film cooling configuration also investigated by Friedrichs et al. [16]. Their design of the new and improved cooling configuration was based on the understanding of endwall film-cooling described in [15]. Using the basic CFD results without coolant ejection, the understanding of endwall film cooling was used to place cooling holes that would provide small aerodynamic losses and better coverage of coolant on endwall. Zhang and Jaiswal [17] measured the film cooling effectiveness by pressure sensitive paint (PSP). They found that the effectiveness increased nonlinearly with mass flow rate and also concluded that the coolant jets interacted with the endwall secondary flows strongly. Mensch et al. [18] measured the heat transfer and predicted a blade endwall film cooling with TBCs by CHT. They addressed that adding TBCs produced a greater improvement in overall cooling effectiveness than the improvements achieved by increasing blowing ratio alone, and allowed the internal cooling to be more effective. Hajmohammadi [19–21] researched the nanofluid application and proposed optimal method for cooling systems.

But for a 3D turbine blade or vane adopting film cooling holes in the leading edge, pressure side, suction side, and endwalls simultaneously, it is still difficult to model nowadays. Especially there are few literatures to guide us detailedly in modeling the endwall film cooling flow [22–25]. In this paper, we developed a simple numerical method to build the endwall film cooling flow domain. Then the cascade flow was modeled by CFD method, and the heat transfer between flow and solid alloy was calculated by CHT. Finally, the temperature and the film cooling effectiveness were compared between the case with or without heat transfer between flow and solid.

2. Description of the turbine vane

The model of the turbine vane is shown in Fig. 1. The film cooling holes lie in the body of the vane and the endwalls. The main parameters of the cascade are listed in Table 1.

There are seven rows of holes in the body of the vane. Three rows of holes lie in the leading edge in stagger arrangement, which is known as showerhead film cooling with the same diameter. Two rows of holes with different diameter lie in the pressure side and suction side, respectively. Also, an inner convection cooling cavity is in the body of the vane. The coolant supply for cooling the main

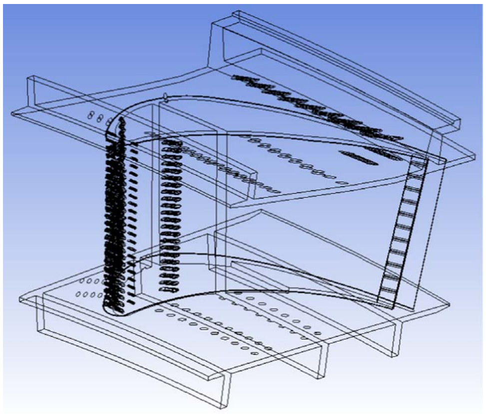

Fig. 1. Geometry of the turbine vane.