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Numerical simulation on film cooling with compound angle of blade leading edge model for gas turbine

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ABSTRACT

Film cooling performances of the cylindrical film cooling holes with different compound angles on the turbine blade leading edge model are investigated in this paper. Several numerical simulation results are compared with available experimental data, under different blowing ratios. Three rows of holes are arranged in a semi-cylinder model which is used to model the blade leading edge. These three rows of holes have a compound angle of 90° in the flow direction, 30° along the spanwise direction. Besides, the two rows on either side of the stagnation row have an additional angle in the transverse direction. Five different film cooling hole compound angles in the transverse direction and four different blowing ratios are studied in detail. The results show that as the blowing ratio increases, the trajectory of the film jets in the leading edge region deviates gradually from the mainstream direction to the spanwise direction, for all cases studied. And film cooling effectiveness increases with the increasing blowing ratio while a slight decrease appears as the blowing ratio approaches 2.0. In this study, the optimal value of M is around 1.4. For the Baseline Case, the overall averaged cooling effectiveness increases by more than 0.1, compared with M = 0.7. The holes with negative additional compound angle have better performance of cooling. On the one hand, the improvement of film cooling effectiveness increases with the increasing negative compound angle, before it reaches -30°. On the other hand, with the increasing blowing ratio, the improvement of the cooling performance due to negative additional compound angle is more significant. For $\gamma = -30°$, the increase of overall averaged cooling effectiveness varies from 1.75% to almost 20%, with the increase of M.

1. Introduction

As the needs arises for higher overall efficiency and higher specific power output, modern gas turbine systems are required to operate at higher turbine inlet temperature, which has already been far beyond the material acceptable level. As a result, more effective cooling schemes must be applied in the turbine vane or blade to protect it from thermal stresses. Film cooling is one of the major cooling methods. In practice, relatively cool air from the compressor stages is injected through holes in the walls of hollow turbine airfoils in order to protect the metal surface from the hot mainstream. Film cooling is applied to nearly all of the external surfaces associated with the airfoils that are exposed to the hot combustion gasses such as the leading edges, main bodies, blade tips, and endwalls. And there have been several studies around it. In Zhang et al. [1] and Li et al. [2], experiments were conducted to consider the effects of leading edge airfoil geometry and film cooling arrangements on endwall film cooling, Becchi et al. [3], studied the film cooling adiabatic effectiveness measurements of pressure side trailing edge cooling configurations. Al-Zurfi and Turan [4] investigated the effect of rotation on film cooling effectiveness and heat transfer coefficient distribution on the suction and pressure sides of a gas turbine blade. Ke and Wang [5] further presented a numerical investigation of pulsed film cooling on a modified NASA C3X, with five rows of cooling hole at leading edge, pressure side and suction side. More information on film cooling can be found in Bogard and Thole [6]. However, in a gas turbine, the leading edge of a turbine airfoil often withstands the highest thermal load since it is upwind to high temperature inflows, and the airfoil failure often occurs in this region due to material damage. According to the study of Bogard and Thole [6], film cooling on vanes and blades generally involves a dense array of coolant holes around the leading edge, referred to as a showerhead. And film cooling yet has very difficult phenomena to predict.

The flow environment around the leading edge is extremely complex with a stagnation mainstream, the curvature of surface, strong pressure gradients and turbulence, as well as interaction

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Nomenclature

d	diameter of the film cooling hole (m)
D	diameter of the semi-cylinder model (m)
M	blowing ratio, $\rho_c U_c/\rho_\infty U_\infty$
p	hole pitch (m)
Re_D	Reynolds number, $\rho_\infty U_\infty D/\mu_\infty$
S	streamwise coordinate originating at the stagnation line (m)
T	temperature (K)
U	velocity (m/s)
x	streamwise coordinate (m)
y	coordinate normal to the model surface (m)
z	spanwise coordinate (m)
RKE	realizable k–ε turbulence model
SST	shear-stress transport turbulence model
negative additional compound angle	rotate the hole clockwise
positive additional compound angle	rotate the hole anticlockwise

Greek symbols

η	film cooling effectiveness, $(T_\infty - T_{aw})/(T_\infty - T_c)$
μ	viscosity (kg/(ms))
ρ	density (kg/m^3)
γ	additional compound angle of the film cooling hole in the transverse direction (°)
Θ	non-dimensional temperature $(T_\infty - T)/(T_\infty - T_c)$

Subscripts

aw	adiabatic wall
c	coolant
w	wall
∞	mainstream

between multiple rows of film cooling holes. Some investigations have been made to study the film cooling performance or the new hole designs over plane surfaces. For example, Liu et al. [7] measured the thermal performances of two kinds of converging slot-hole with different divergence angles using a transient liquid crystal measurement technique. Ramesh et al. [8] analyzed the thermal performance of tripod film cooling holes with and without manufacturing features. Khajehhasani and Jubran [9] made a numerical investigation of film cooling performance through variations in the location of discrete sister holes. Wang et al. [10] studied the effect of surface deposition and mist injection on film cooling. They found that mist injection can significantly enhance film cooling performance. Li et al. [11] compared the dimensionless temperature distributions for several turbulence models using a single jet model.

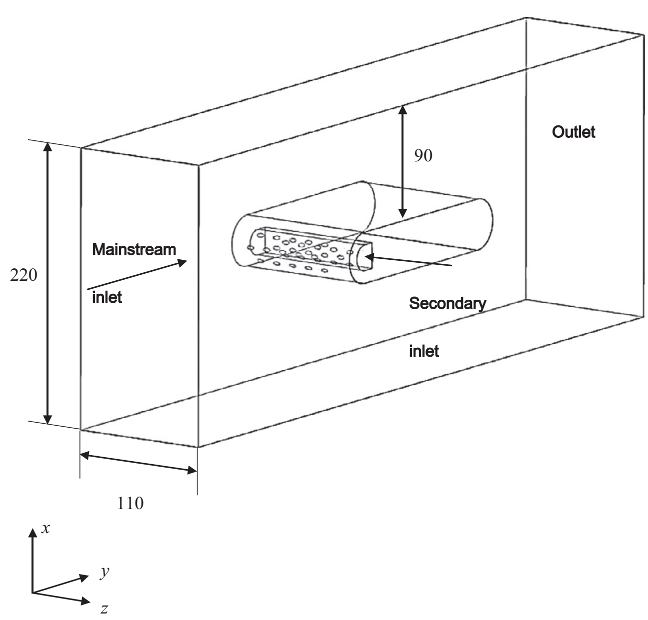

Fig. 1. Computational model. All dimensions are given in millimeters.

Additionally, cylinder or semi-cylinder model has been often deployed by researchers to model the leading edge of blade, which had been proved to be an effective method. In this way, the leading edge film cooling can be investigated easily under different film-hole configurations and flow conditions. Cylindrical hole is the basic film-hole geometry for the leading edge [12]. Many investigations show that the shaped hole has extensive benefits to the improve of the film cooling performance. So a majority of the investigations studied cylindrical holes and shaped holes. Ou and Rivir [13] studied film cooling effectiveness and heat transfer coefficients on a large scale symmetric circular leading edge with three rows of film cooling holes. The configuration has a smaller injection angle (20°) and a larger hole pitch according to the hole diameter. They found that the increase of the turbulence intensity has a negative influence on film cooling effectiveness as well as the Frössling number for all blowing ratios at Re = 30,000. Kim et al. [14] studied the flow characteristics of the film-cooled turbine blade using a cylindrical body model with three different arrangements of injection holes. Ahn et al. [15] presented the influence of rotational speed, blowing ratio, and vortices on the film cooling effectiveness distribution around the leading edge region. Their result indicated that different rotation speeds significantly change

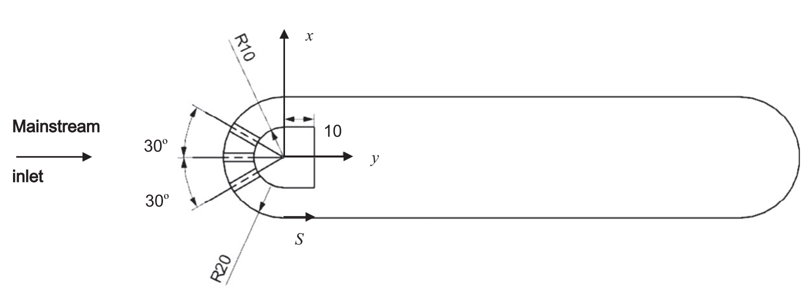

Fig. 2. Configuration of the test model. All dimensions are given in millimeters.