NUMERICAL STUDY ON FLAT PLATE AND LEADING EDGE FILM COOLING

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ABSTRACT

This study describes a 3-D computation for film cooling effectiveness investigation using Fluent commercial code, version 6.2. Two configurations are examined: (1) Flat plate, and (2) Semi-cylindrical leading edge with a flat after-body. Three different RANS turbulence models and DES based on Spalart-Allmaras model are utilized to see the difference in accuracy between DES and RANS approaches. Similar to the previous RANS simulation, lateral spreading of film cooling is under-estimated in the RANS simulation, while in the DES, lateral spreading of film cooling is enhanced and shows adequate agreement with the previous experiments.

The effects of velocity magnitude and orientation of plenum flow on film cooling effectiveness are also studied in the flat plate configuration. The plenum flow is eventually found to have a strong impact on the flow structure in the cooling pipe, and the distorted velocity profile in the pipe consequently lowers film cooling effectiveness, in particularly at high blowing ratio.

INTRODUCTION

To increase thermal efficiency, advanced gas turbine is designed to operate at increasingly higher temperature. Since the gas temperature exceed the allowable material temperature, cooling techniques of turbine components are increasingly important. Film cooling is a standard method applied to turbine blades and vanes, whereby cold air injected from small holes forms a thin layer over walls and protects the wall from high temperature gases.

Flow fields around a film cooling hole have been studied extensively [1, 2] and complex structure of vortices was reported (see Fig. 1). Among those vortices, the counter-rotating vortex pair (CRVP) is suggested to have a dominant impact on the film cooling performance [3]. This is because CRVP is less dissipative and contributes directly to the mixing between the main stream and the cooling flow.

Since most of the film-cooling flow fields are turbulent, computational methods that could be adopted for the analysis of film cooling are, direct numerical simulation (DNS), large eddy simulation (LES), simulation based on Reynolds Averaged Navier-Stokes (RANS) and detached eddy simulation (DES) that is a kind of combination of RANS simulation and LES. Among these methods, DNS and LES have the highest potential to provide the reliable results. Meanwhile, RANS simulation has an advantage in short turn-around time suitable for designing usage. Fig. 2 compares the number of grid points required for each simulation [4]. RANS simulation requires smaller number of grid points than those required in DNS and LES.

A number of RANS simulations have been carried out on film cooling flow fields on a flat plate. Na et al. [5], Leylek et al. [6] reported that laterally averaged film effectiveness showed good agreement with the experimental results, but the RANS simulation under-estimated lateral spreading of film cooling. Due to the today’s development of computing capabilities, LES have been applied to the film cooling flow fields. Tyagi and Acharya [7, 8] performed LES of film cooling flow from inclined holes considering two hole lengths, \(L/d=1.75\) and \(L/d=6\). Recent studies by Peet et al. [9], Mizukami et al. [3] performed LES study of film cooling from...
realistically short cylindrical holes of \( L/d = 3.5 \) and reported that considerable improvement was obtained by the LES. Nevertheless, much should be made on numerical studies on film cooling to improve their predictability.

The main objective of this study is therefore to clarify the reliability of DES and RANS simulation for the prediction of film cooling effectiveness. Film cooling flow fields around a circular hole on a flat plate were analyzed by the RANS simulation with \( k-\omega \) type turbulence models, they are shear-stress transport (SST) model [10], \( k-\omega \) model with the modification of Kato-Launder [11] and \( k-\omega \) with time-scale bound [12], as well as the DES [13] based on Spalart-Allmaras (S-A) model [14]. The results were compared with each other and with the previous experimental and numerical results [3, 9, 15-19]. In preparation for the simulations of film cooling flow on semi-cylindrical leading edge, the effect of plenum flow on film cooling effectiveness was also investigated by the RANS simulation.

**NOMENCLATURE**

- \( \alpha \) : holeaxis angle from the stagnation line
- \( BR \) : blowing ratio, \( = \rho_c U_c/\rho_m U_m \)
- \( d \) : cooling hole diameter
- \( DR \) : Density ratio, \( = \rho_c/\rho_m \)
- \( dt \) : computational time step
- \( D \) : leading edge diameter
- \( \eta \) : film effectiveness, \( = (T_{ad} - T_m)/(T_c - T_m) \)
- \( L \) : cooling hole length
- \( LE \) : leading edge
- \( \theta \) : dimensionless temperature, \( = (T_f - T_m)/(T_c - T_m) \)
- \( Re \) : Reynolds number
- \( \rho \) : density
- \( t \) : time
- \( T \) : temperature
- \( TE \) : trailing edge
- \( TL \) : turbulence level
- \( u \) : instantaneous \( x \)-velocity
- \( U \) : mean velocity
- \( v \) : instantaneous \( y \)-velocity
- \( w \) : instantaneous \( z \)-velocity

**subscripts**

- \( ad \) : adiabatic wall
- \( c \) : cooling air
- \( center \) : center line \((y/d=0)\)
- \( lat \) : laterally averaged \((-1.5\leq y/d\leq1.5)\)
- \( spa \) : spatially averaged \((0\leq x/d\leq11,-1.5\leq y/d\leq1.5)\)
- \( f \) : fluid
- \( m \) : main stream
- \( rms \) : root mean square

A large-scaled test model of a typical leading edge with cooling holes is constructed by use of acrylic-resin semi-circular cylinder and plates. Film cooling effectiveness over the leading edge was measured by a comb-like thermo-probe consisting of a number of thermocouples and thermochromic liquid crystal [20]. Experimental results are compared with the results of RANS simulation with \( k-\omega \) SST model and the DES based on S-A model.

**GRID SYSTEM**

**FLAT PLATE CONFIGURATION**

A Flat plate configuration is taken from the experimental study of Kohli et al. [15]. Schematic view of computational domain is shown in Fig. 3. The geometry of the computational domain is almost identical to the ones used in the simulations of Na et al. [5], Leylek et al. [6] and Mizukami et al. [3]. The domain consists of a main stream region, a circular cooling
hole and a plenum chamber. Cooling jet emerged from the plenum chamber through the circular cooling hole. Working fluid is air. The cooling hole has a diameter of \( d = 12.7 \text{mm} \), length of \( L = 3.5d \) and an inclination angle of 35 degrees with respect to the main stream. Periodic condition is imposed to the lateral direction so that only one film cooling hole needs to be examined. The \( x \), \( y \) and \( z \) coordinates are taken to be stream-wise, lateral and normal to wall, respectively. The origin of axes is the trailing edge of the cooling hole exit.

The flow conditions are summarized in Table 1. Temperatures of main stream and cooling flow are 298K and 188K, respectively. Density ratio, DR, is 1.66. The averaged velocity of main stream, \( U_m \), is 20m/s. Similar to the simulations of Na et al. [5], velocity profile is uniform at the inlet of main stream region, and turbulence boundary layer develops from the leading edge of flat plate. The velocity magnitude at the plenum inlet is adjusted so that the blowing ratio, BR, becomes 0.5. The velocity profile at the plenum inlet is also uniform. All walls are adiabatic and back pressure at the outlet boundary of the main stream region is set to be 1 atm. Reynolds number based on the main stream velocity and the cooling hole diameter, \( Re_m \), is 16,400, and Reynolds number based on the inlet velocity of plenum chamber and the film cooling hole diameter, \( Re_c \), is 336.

To check the grid dependency of the results, three grids, A, B and C were employed in the RANS simulations. Fig. 4 shows the close up view of the grid B. The numbers of cells in three grids are as follows: grid A: about 1.2 million, grid B: about 2.4 million and grid C about 4.2 million. Grid A is the coarsest version and grid C the finest version. A grid system employed in the DES was obtained by refining the grid B around the film cooling hole and the downstream. The number of cells in the grid for the DES is 5.8 million. For all the grids, \( y^+ \) of the cell center on the flat plate was less than unity.

### Table 1 Numerical conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Blowing ratio, BR</td>
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<tr>
<td>Main stream Reynolds number, ( Re_m ) [-]</td>
<td>16400</td>
</tr>
<tr>
<td>Main stream static temperature, ( T_m ) [K]</td>
<td>298</td>
</tr>
<tr>
<td>Cooling air static temperature, ( T_c ) [K]</td>
<td>188</td>
</tr>
</tbody>
</table>

**LEADING EDGE CONFIGURATION**

Fig. 5 shows the computational domain of semi-cylindrical leading edge model with a flat after-body. This configuration is taken from the experiment described below. The experimental apparatus used in this study is shown in Fig. 6. The computational domain consists of a primary domain, cooling holes, a plenum, and a secondary flow chamber. Within the cylindrical wall of 80mm diameter \( (D=10d) \) are a plenum and three rows of film cooling holes arranged in a staggered fashion. The diameter of each hole is 8mm \( (d=8\text{mm}) \). The inclination angle of holes is 30 degrees relative to the span-wise direction. Periodic condition is imposed to the span-wise direction so that only three film-cooling holes need to be examined. The separation angle between the hole 1 (row 1) and hole 2 (row 2) in the \( x-y \) plane is 30 degrees and the separation angle between hole 2 (row 2) and hole 3 (row 3) in the \( x-y \) plane is 35 degrees. The pitch between the holes is 31 mm \( (3.86d) \) (see Figs. 5 and 6).

The number of cells in the total domain is about 1.4 million (0.6 million in the primary domain, 0.5 million in the cooling holes, 0.1 million in the plenum, and 0.2 million in the secondary chamber and the connecting duct.) Same grid system was employed in both the RANS simulation and the DES.

Working fluid is air. The flow conditions are summarized in Table 2. Mass flux at the inlet of secondary flow chamber is set to be 0.03kg/s, and blowing ratio was adjusted to BR=1.0 and BR=2.0 by controlling the back pressure at the plenum outlet. Since the secondary air (cooling air) is heated in the
experiment shown in Fig. 6, the temperature of cooling flow was set to be higher than that of the main stream. Static temperatures of main stream and cooling flow are 291K and 321K, respectively. Reynolds number based on the main stream velocity and the cooling hole diameter, $Re_m$ is 8,550.

![Fig. 5 Schematic view of leading edge model](image1)

### Table 2 Numerical conditions

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<table>
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<tr>
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<tbody>
<tr>
<td>Blowing ratio (hole average), BR [-]</td>
<td>1.0 / 2.06</td>
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<tr>
<td>Blowing ratio (row 1) [-]</td>
<td>0.9 / 2.0</td>
</tr>
<tr>
<td>Blowing ratio (row 2) [-]</td>
<td>0.96 / 2.0</td>
</tr>
<tr>
<td>Blowing ratio (row 3) [-]</td>
<td>1.2 / 2.2</td>
</tr>
<tr>
<td>Main stream Reynolds number, $Re_m$ [-]</td>
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</tr>
<tr>
<td>Main stream static temperature, $T_m$[K]</td>
<td>291</td>
</tr>
<tr>
<td>Cooling air static temperature, $T_c$[K]</td>
<td>321</td>
</tr>
</tbody>
</table>

Fig. 5 Schematic view of leading edge model

Fig. 6 Experimental setup to simulate leading edge film cooling

![Fig. 6 Experimental setup to simulate leading edge film cooling](image2)

### Numerical Methods

#### RANS

Governing equations are compressible Navier-Stokes equations and conservation equation. Three different turbulence models were employed for the purpose of validation. They are shear-stress transport (SST) model [10], $k-\omega$ model with the modification of Kato-Launder [11], and $k-\omega$ model with time-scale bound [12]. Solutions to the Naier-Stokes equations, the conservation equation and the three turbulence models were obtained by using commercial code, Fluent version 6.2 [21] with 3rd order MUSCL scheme [22]. SIMPLE algorithm [23] was used to generate solutions.

#### DES

Detached eddy simulation [13] based on the Spalart-Allmaras model [14] was performed. Switching between from RANS to LES is determined by the DES length scale, $l$:

$$l = \min(d_w, C_{DES} \Delta)$$

where $d_w$ is the distance to the closest wall, and $C_{DES}$ is constant ($C_{DES} = 0.65$). This length scale is also based on the largest dimension of the local grid cell.

$$\Delta = \max(dx, dy, dz)$$

Fig. 7 shows the switching between from RANS to LES for the flat plate configuration. Blue region was analyzed by LES and red region was analyzed by the RANS simulation with S-A model [14]. In the red region, there were about 15 cells in z-direction (normal direction to the wall).

To generate solutions, SIMPLE algorithm was used. Simulations were advanced with the computational time step $dt = 0.002 d/U_m$, statistics were accumulated over the period of $t=8d/U_m$. Spatial difference terms were evaluated by 2nd order central-differencing scheme.

### Experimental Methods

A large-scaled test model of a typical leading edge with cooling holes was constructed by use of acrylic-resin semicircular cylinder and plat plates to obtain experimental data. The model was placed inside the test duct connected to the contraction nozzle. The model is equipped with a plenum chamber to supply the secondary air. Fig. 6 shows the experimental setup to simulate leading edge film cooling.

Film cooling effectiveness over the leading edge was measured by a transient method using thermochronic liquid.
Table 3 Experimental conditions

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<table>
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<tbody>
<tr>
<td>Blowing ratio (hole average), BR [-]</td>
<td>1.06 / 2.04</td>
</tr>
<tr>
<td>Main stream Reynolds number, Rem [-]</td>
<td>8550</td>
</tr>
<tr>
<td>Main stream static temperature, T_m [K]</td>
<td>289</td>
</tr>
<tr>
<td>Cooling air static temperature, T_c [K]</td>
<td>321</td>
</tr>
</tbody>
</table>

Crystal [20], where the secondary air was then heated. As for the film cooling effectiveness, a comb-like thermo-probe consisting of a number of thermocouples was also employed to acquire the quasi-adiabatic wall temperature. Experimental conditions are summarized in Table 3.

RESULTS AND DISCUSSIONS

FLAT PLATE CONFIGURATION

GRID SENSITIVITY STUDY

Fig. 8 shows the results obtained by three grids A, B and C for the laterally averaged film cooling effectiveness at BR=0.5. The k-ω SST model was adopted in the RANS simulations. The results of previous experiments [15] are also plotted in the figure. Experimental conditions of the reference [15] are almost identical to the present computation. Good agreement is shown among the numerical results except just downstream of film cooling hole. The prediction with the coarsest grid A presents higher film cooling effectiveness than those with the grid B and the grid C. The reason for this trend is as follows. The cooling flow separates at the trailing edge of the cooling hole exit and separation vortex is observed just downstream of cooling hole. Due to the lack of grid cells in the grid A, the flow separation could not be resolved and higher film cooling effectiveness was predicted.

Though the number of cells is quite different between the grid B and the grid C, similar results are obtained. From Fig. 8, the grid B is found to be optimal. Hereafter, the grid B was employed for the RANS simulations.

FILM COOLING EFFECTIVENESS

Fig. 9 compares the DES with the RANS simulation on the laterally averaged film cooling effectiveness. The previous experimental results [15-18] are also plotted in the figure. The experimental results show some deviation near the injection location. This deviation can be attributed to the different flow parameters and the different length-to-diameter ratio used in these studies. While, Pedersen et al. [17] and Foster et al. [18] used long tubes, Sinha et al. [16] used a hole length of \( L/d = 1.75 \), and Kohli et al. [15] used a hole length of \( L/d = 3.5 \). Solid line and broken line represent the LES results by Mizukami et al. [3] and Peet et al. [9], respectively. They used a hole length of \( L/d = 3.5 \).

The film effectiveness obtained by the RANS simulations is in accordance with the experimental results. Differences among the results by three turbulence models are negligible. k-ω SST model will be selected and will be referred to as SST model from this point on. The DES result shows adequate agreement with the experimental results except for the downstream of cooling hole, where the DES results shows a slightly higher film cooling effectiveness compared to the RANS results.

Predictions of film cooling effectiveness on the center line of the flat plate are plotted in Fig. 10. The results of previous experiments [15-17] and LES simulations [3, 9, 19] are also
plotted in the figure. The LES results agree well with the experiments. In the RANS simulation with the SST model, the center line film cooling effectiveness is much higher than the experimental results. But an improvement is observed in the DES result, where the film cooling effectiveness on the center line becomes closer to the experiment at $x/d=5$.

Fig. 11 shows the lateral distribution of film cooling effectiveness at $x/d=3$, 10 and 15. The results of the RANS simulation with the SST model and the DES are shown in the figures. Closed circle represents the experimental results obtained by Sinha et al. [16]. It is apparent that lateral spreading of film cooling is under-estimated in the SST simulation. On the contrary, lateral spreading of film cooling is enhanced in the DES. Although the DES result shows higher film cooling effectiveness at $x/d=3$, the distributions of film cooling effectiveness matches well with the experimental results at $x/d=10$ and 15. As a whole, in Fig. 11, much improvement is obtained by use of the DES in the prediction of film cooling effectiveness. The DES result and the experiment shows signs of inconsistence at $x/d=3$. This might come from the difference of vortex structure after the cooling hole exit, that should be strongly influenced by the turbulence level around the cooling hole.

![Fig. 10 Film cooling effectiveness on center line](image)

![Fig. 11 Lateral distribution of film cooling effectiveness](image)

Turbulence level (obtained in DES), $TL$, on the center plane is shown in Fig. 12. The turbulence level was defined as $(u_{rms}^2+w_{rms}^2)^{1/2}/U_{ref}$. Since turbulence was not imposed at the inlet of the main stream region in the DES simulation, the distribution of $TL$ is much different from the one measured by Pietrzyk et al. [24]. This might be one of reasons for the over prediction of film cooling effectiveness at $x/d=3$ (see Figs. 9-11). To be discussed later, the temperature distribution at $x/d=3$ was strongly influenced by the vortex structure. The turbulence level should have some effects on the flow separation and formation of vortex.
TEMPERATURE DISTRIBUTION

Fig. 13 visualizes dimensionless temperature, $\theta$, in the cross sections of $x/d=3$ and $x/d=10$. Top and middle figures correspond to the results of the DES (the top figure shows instantaneous temperature distribution and the middle figure shows time averaged temperature distribution), and bottom figure corresponds to the results of the RANS with SST. Quasi-symmetrical temperature distribution against the center plane is observed in the middle and bottom figures, while in the top figure, asymmetrical and distorted temperature distribution is shown. The finding means that the cooling flow fluctuates in the cross sections.

A round-shaped distribution is observed in the cross sections of the SST result, while a triangle-shaped distribution is observed in the DES. Compared to the SST result, high film cooling effectiveness region is observed around $|y/d|=0.5$ at $x/d=3$ in the DES result (see Fig.13).

Fig. 14 shows the contour of turbulence level at $x/d=3$ for the DES. Turbulence level, $TL$, is defined here as \( \left( \frac{v_{\text{rms}}^2 + w_{\text{rms}}^2}{U_{\infty}} \right)^{0.5} \). The turbulence level is not large around $|y/d|=0.5$, therefore, there must be another factor that accounts for the spreading of cooling air around $|y/d|=0.5$ at $x/d=3$.

VORTEX STRUCTURE

To explain the difference in the cross-sectional temperature distribution between the SST and the DES results, velocity fields are visualized in Fig 15, which shows the velocity vectors of secondary flow at $x/d=3$. Top figure corresponds to the SST result, while the bottom figure corresponds to the DES (time averaged). In the SST result, counter rotating vortex pair (CRVP) is observed clearly, and the velocity vector is directed inward over the entire near-wall region. The inward velocity vectors seem to suppress the lateral spreading of film cooling. On the contrary in the DES results, counter rotating vortices against the CRVP are observed just outside the CRVP. Due to the outside vortices, velocity vectors near the wall directed to outward around $|y/d|=0.5$. The outward velocity seems to be essential for the spreading of film cooling in the lateral direction.

As shown in Fig.16, the counter vortices against the CRVP were also observed in the result of LES by Mizukami et al. [3].
EFFECTS OF FLOW IN PLENUM

In this section, effects of plenum flow on the film cooling effectiveness were numerically investigated. Main concern of this section is to qualitatively clarify how plenum flow affects the film cooling effectiveness. In order to reduce the computational costs and time, the RANS simulations with the SST model were performed here.

Fig.17 shows the relationship between spatially averaged film cooling effectiveness, $\eta_{spa}$, and BR. $\eta_{spa}$ is obtained by axially and laterally averaging the film cooling effectiveness in the area of $0 \leq x \leq 11d$ and $-1.5d \leq y \leq 1.5d$. Case 1 is above-mentioned results in which cooling fluid is supplied from the bottom of plenum chamber. The velocity of cooling flow is very small in case 1. In cases 2 and 3, cooling flow is induced in parallel to a main stream. Reynolds number based on the mean velocity at plenum inlet and cooling hole diameter, $Re_c$, and the orientation of plenum flows are summarized in Table 4. Reynolds number based on the main stream velocity and the cooling hole diameter, $Re_m$ is 16,400.

From the comparison among cases 1-3, it is apparent that parallel orientation of the plenum flow improves the film cooling effectiveness except for BR=0.3. From the comparison between case 2 and 3, the film cooling effectiveness increases with the increase on velocity magnitude in the cooling passage. This trend is clearly shown at high BR conditions, while no increase is observed at BR=0.3.

Distributions of film cooling effectiveness for case 1 and case 3 are shown in Figs.18 and 19, respectively. Top figure corresponds to BR=0.3, middle figure corresponds to BR=0.5, and bottom figure corresponds to BR=1.0. From the comparison of Figs.18 and 19, a clear improvement is observed at BR=1.0.

In Figs. 20 and 21, velocity fields on the center line cutting plane were visualized and hole-axial velocity magnitude is colored at the cross sections of $z/d=-0.5$ and $z/d=-1.5$. The hole-axial velocity is normalized by the main stream velocity. Fig. 20 shows the flow fields at BR=0.3, and Fig. 21 shows the flow fields at BR=1.0. Figure (a) corresponds to case 1, (b) corresponds to case 2, and (c) corresponds to case 3, respectively.

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**Table 4 Re and orientation of plenum flow**

<table>
<thead>
<tr>
<th>Case</th>
<th>$Re_c$</th>
<th>Orientation</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;800</td>
<td>Vertical</td>
</tr>
<tr>
<td>2</td>
<td>5040</td>
<td>Parallel</td>
</tr>
<tr>
<td>3</td>
<td>10080</td>
<td>Parallel</td>
</tr>
</tbody>
</table>
Fig. 18 Film cooling effectiveness (case 1)

Fig. 19 Film cooling effectiveness (case 3)

Fig. 20 Velocity fields in cooling pipe (BR=0.3)
Flow structure in the cooling pipe is quite different among the cases at BR=0.3 (see Fig. 20). In case 1, cooling flow separates at the trailing edge of the cooling hole entrance. Jet-like flow is observed near the windward wall of the cooling hole (Fig. 20(a)). While in the case 3, flow separation occurs at the leading edge of the pipe entrance and jet-like flow is observed near the leeward wall (Fig. 20(c)). Flow structure is drastically changed from case 1 to case 3. Case 2 can be regarded as the transition from case 1 to case 3.

At BR=1.0, fundamental flow structure in the cooling hole is similar among the cases (see Fig. 21). Flow separation occurs at the trailing edge of the cooling hole entrance and jet-like flow is observed near the windward wall of the cooling hole in all the cases. Low momentum region emerged near the opposite side of the jet-like flow. The area of low momentum region observed in case 1 is larger than that observed in case 3. In case 1, jet-like flow is developing more pronouncedly than other two cases. Due to the jet-like flow, the cooling flow tends to lift off at the cooling hole exit, and consequently small film cooling effectiveness was observed in case 1.

It is interesting that even though flow structure in cooling pipe drastically changed, there was very small difference in film cooling effectiveness between case 1 and case 2 at BR=0.3. On the contrary, film cooling effectiveness differed dramatically from case 1 to case 3 at BR=1.0, even though qualitative flow structure in the cooling pipe is almost the same. At the high BR conditions, due to the large momentum of cooling flow, the velocity profile in the cooling hole seems to have a strong influence on the flow structure downstream of the cooling hole exit (generation of separation vortex at the trailing edge of cooling hole) as well as the film cooling performance.

**LEADING EDGE CONFIGURATION**

As mentioned above, plenum flow strongly influences the film cooling effectiveness at high BR conditions. In the simulations of semi-cylindrical leading edge model, the flow fields not only in the primary domain and the cooling holes but also in the connecting duct and the secondary flow chamber were calculated.

Fig. 22 shows the experimentally measured film cooling effectiveness on the surface of semi-cylindrical leading edge model. Fig. 22 (a) shows the film cooling effectiveness around the downstream of row 3 (-90°<α<-15°). The left hand side figure corresponds to the film cooling effectiveness measured with thermocouple, and the right hand side figures correspond to the ones measured with liquid crystal technique. Although a little difference is observed at the leading edge of row 3, the distribution of film cooling effectiveness qualitatively agrees between the measurement data using thermocouples and liquid crystal. Fig. 22 (b) shows the film cooling effectiveness around the downstream of row 1 (15°<α<90°). Temperature fields were measured with liquid crystal.

Figs. 23 and 24 show the results of the DES and the RANS simulation with the SST at BR=1.0 and 2.0, respectively. In Figs. 22-24, although similar distributions of film cooling effectiveness are observed, much higher film cooling effectiveness regions are appeared in the SST results around the downstream of row 1 (30°<α<90°) for BR=2.0 (see Fig. 23), and the downstream of row 3 (-90°<α<-60°) for BR=1.0 (see Fig. 24).
Fig. 22 Measured film cooling effectiveness

Fig. 23 Film cooling effectiveness (BR=2.0)

Fig. 24 Film cooling effectiveness (BR=1.0)
Fig. 25 Laterally averaged film cooling effectiveness

Fig. 25 shows spanwisely averaged film cooling effectiveness. From Fig. 25, it is apparent that the DES showed the closer results with the experiments than the RANS results around 30º<α<90º (BR=2.0) and -90º<α<-60º (BR=1.0).

CONCLUSIONS

Reliability of the RANS simulations with k-ω type turbulence models and the DES based on S-A model for the prediction of film cooling effectiveness was investigated in the flat plate model and the leading edge model of turbine blade. Numerical results were compared with the previous experiments and the measurement data with thermocouples and a liquid crystal. Conclusions are summarized as follows.

1. In the flat plate configuration, both the RANS simulations and the DES showed adequate agreement with the experiments in the laterally averaged film cooling effectiveness.
2. In the DES, counter rotating vortices against the CRVP were observed. Due to the vortices, the lateral spreading of film cooling effectiveness was enhanced.
3. Distorting the velocity profile in the cooling hole, cooling flow orientation and velocity magnitude in plenum chamber was found to strongly influence film cooling effectiveness at high BR conditions.
4. In the semi-cylindrical leading edge configuration, DES showed better agreement with the experiments than the RANS simulation.

REFERENCES


