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STUDY ON THE THERMAL AND FLOW FIELDS OF SHAPED FILM COOLING HOLES

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ABSTRACT

Blades and vanes for advanced gas turbines are cooled externally by film cooling. In order to attain higher film cooling effectiveness, it is important to understand the mixing phenomena of film cooling air with mainstream hot gas. Today, shaped film-cooling holes are used as film cooling holes, but the shaped film-cooling holes have many geometric parameters and the effects have not been studied entirely. In addition, instantaneous flow structure of film cooling is extremely complicated because it accompanies many vortices, which are generated by a strong shear at the interface between the mainstream and coolant jet. In this paper, using the optimized shaped film-cooling holes by CFD and a conventional circular hole, the detailed mixing mechanism of film cooling air with mainstream was examined by LIF and PIV using a low-speed wind tunnel. By this method, instantaneous field of film cooling effectiveness was successfully obtained with high resolution, which clarifies fine structure of temperature field at the shear layer. In addition, unsteady numerical simulations were performed to examine the detailed mechanism of the mixing process, using the Detached Eddy Simulation as a LES/RANS hybrid model.

EXPERIMENTAL APPARATUS

The detailed mixing mechanism of film cooling air with mainstream has been studied using a low-speed wind tunnel and an optical measurement system shown in Figure 1. The wind tunnel has an inlet nozzle with a 9:1 contraction ratio and the test section is 300 mm wide, 300 mm height, and 1950 mm long. The main stream speed can be varied from 0 to 40 m/s. For the free-stream velocity of 20 m/s, flow at the inlet shows excellent spatial uniformity, with a free stream turbulence level less than 0.36% at the inlet of the test section.
Shaped film cooling holes geometries firstly have been optimized by CFD using RANS. And the film cooling effectiveness has been measured for four different kinds of scale-up models of film cooling holes shown in Figure 2 including a conventional circular hole. The models were made of Bakelite. The guide channels to the exits of film cooling holes were inclined at 30 degree toward the main flow direction. The shaped holes are composed of a round tube section with an exit, where a fan-shaped diffuser exists with 15-degree divergence angles on the both lateral sides. The shaped hole (a) is the base geometric form. The shaped hole (b) has no diffused angle in the flow direction. The shaped hole (c) has the flow channel expanded from the deeper point than the shaped hole (a). The diameter of the guide channel was 5 mm.

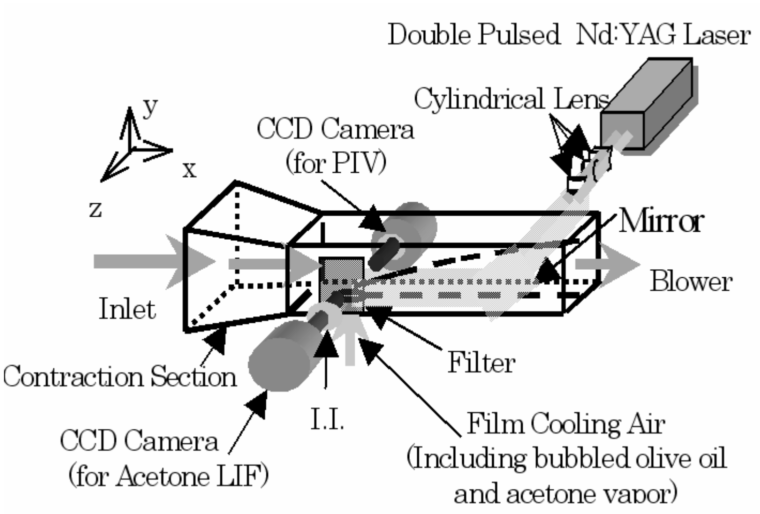

Figure1. Experimental apparatus and optical measurement

Two dimensional velocity fields were measured by PIV (Particle Image Velocimetry) and the film cooling effectiveness distributions were measured by acetone LIF (Laser Induced Fluorescence) and an array of K-type thermocouples mounted on a two-axis high accuracy traversing system.

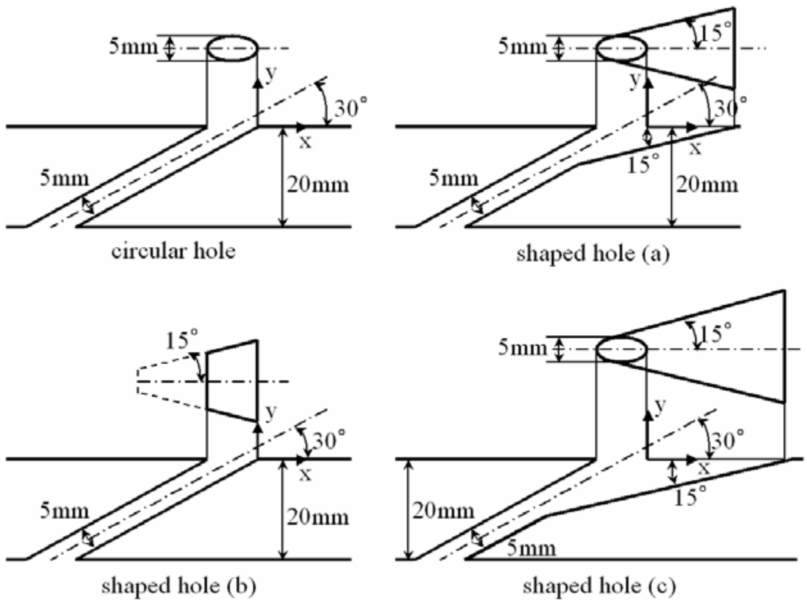

Figure 2. Film cooling hole geometries

NUMERICAL PROCEDURE

Numerical simulations has been conducted to examine the detailed mechanism of the mixing process of the mainstream and film cooling air blowing through four different film cooling holes geometries shown in Figure 2, and to compare the predicted results with the measured data obtained by PIV and acetone LIF. In this study, Detached Eddy Simulation (DES), which is a RANS/LES hybrid simulation, was applied to solve the unsteady mixing phenomena of film cooling air for the shaped holes (b) and (c), which have shown the best and the second-best performance in the experiment. The domain includes a plenum chamber, a coolant hole, and a mainstream region. Multi-block structured grid is basically used except for the inside of the shaped hole (c), where unstructured grids were applied to avoid the high grid skewness. The total number of cells for the cases of shaped holes (b) and (c) are 920,000 and 1,600,000, respectively. All simulations were performed using FLUENT 6.3 with the SIMPLE algorithm. A bounded central differencing scheme, which is a blended scheme of the central difference, 2nd-order upwind scheme, and 1st-order upwind scheme, was applied to discretize the convection terms of momentum equation.

RESULTS AND DISCUSSION

Figure 3 shows the averaged film cooling effectiveness distribution along the stream-wise direction at the blowing ratio M = 1.0. This figure indicates that the shaped film cooling hole (b) has the highest film cooling effectiveness in the four geometries.

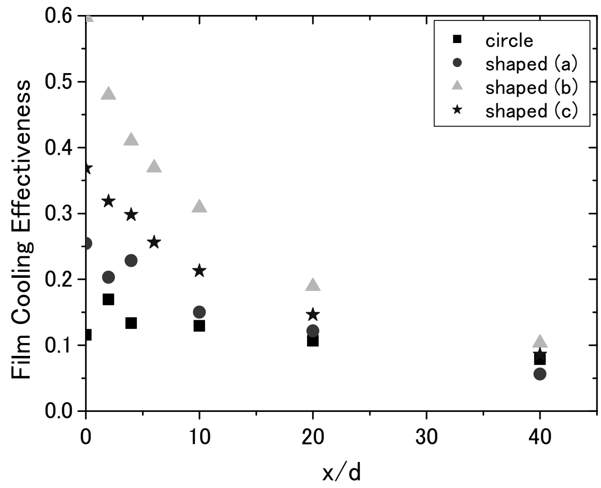

Figure 3. Averaged film cooling effectiveness at M=1.0

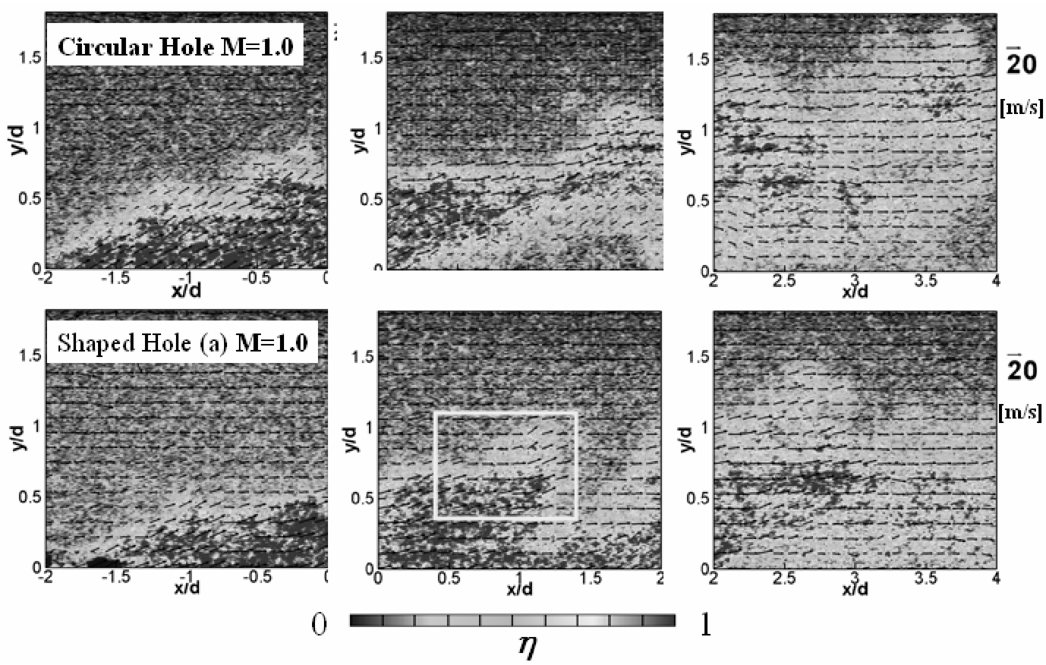

Figure 4. Instantaneous and simultaneous distributions of velocity vectors and film cooling effectiveness measured by acetone LIF and PIV

The mixing behaviors between the film cooling air and the mainstream have been measured simultaneously and instantaneously by acetone LIF and PIV.
Figure 5 shows the comparison between the numerical result by DES and the experimental one at the blowing ratio M = 0.5, for the shaped hole (c). As the figure indicates, DES prediction shows strong adhesion of the film cooling air on the wall in comparison with the experimental result. This arises from the prediction of weak diffusion of film cooling air into mainstream.

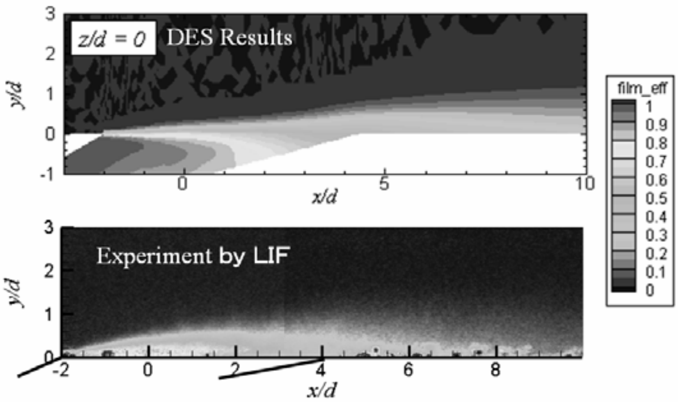

Figure 5. Comparison of film cooling effectiveness between DES result and LIF for shaped hole (c) at M=0.5

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