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COOLING EFFECTIVENESS MEASUREMENTS OF FILM COOLING CONFIGURATION ON THE SUCTION AND PRESSURE SURFACE OF NOZZLE GUIDE VANE

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ABSTRACT: Detailed experiments were carried out to obtain the film cooling effectiveness distribution on the suction and pressure surface of a nozzle guide vane provided with two pairs of film cooling hole rows on each surface. Experiments were carried out varying the blowing ratio in the range of 0.35 to 2.5 and coolant to mainstream density ratio in the range of 0.97 to 1.57. The results indicate that the magnitude of the adiabatic effectiveness was lower and the decay of adiabatic effectiveness faster on the pressure surface in comparison to those on the suction surface indicating the effect of surface radius of curvature. The film cooling effectiveness data obtained on the suction surface indicate that at higher coolant to mainstream density ratio the film effectiveness decays faster and at larger downstream distances the magnitude was lower than that for lower coolant to mainstream density ratio. The results also indicate that on the suction surface in the case of flow through both the two pairs of hole rows the effectiveness distribution downstream of the second pair of row can be estimated with satisfactory accuracy using the correlation for additive effect of film cooling. Film cooling effectiveness data can be used to estimate the adiabatic wall temperature and hence the estimation of blade metal temperatures.

1. INTRODUCTION

Film cooling finds increasing application in the cooling of turbine blades. A number of factors influence the cooling performance of film cooling configuration. Main geometric parameters are the inclination angle of film cooling hole to the surface and free stream, radius of curvature of the surface, hole to pitch diameter ratio and the main flow parameters are coolant to mainstream density ratio, blowing ratio, pressure gradient and free stream turbulence. The estimation of heat flux to the wall in the region of film cooling requires information on the distribution of adiabatic film cooling effectiveness and the local heat transfer coefficient under the influence of film cooling flow. The film cooling performance of various film-cooling configurations have been extensively studied using simple flat plate test facilities. Majority of these investigations are for single row of film cooling holes. These studies have been mainly helpful in identifying the effect of various influencing factors on the film cooling performance of film cooling configurations. Modern cooled turbine blades employ multi row film cooling configurations. In actual turbine blade, the performance of film cooling configurations provided in it is influenced by the radius of curvature of the blade surface and the effect of upstream film cooling. Ito et al [1] studied the film cooling performance of a row of jets on a gas turbine blade in a cascade facility to evaluate the effect of radius of curvature on adiabatic film cooling effectiveness. On the convex surface, for small momentum flux ratio, the effectiveness observed was higher than that for flat plate. A reduction in effectiveness was observed at higher momentum flux ratios. On the concave wall the effects of curvature were the reverse of those observed on the convex surface. Schwarz and Goldstein [2] observed in their experiments with concave surface a behavior similar to that mentioned above. The above results indicate that the performance of film cooling configuration on the turbine blade concave and convex surfaces would depend on the injection angle and blowing ratio. The above experiments were carried out with single row of holes. Polanka et al [3] studied the effect of showerhead injection on film cooling effectiveness for a downstream row of holes. It was observed that the shower head injection results in significant degradation of the adiabatic effectiveness performance of downstream row of holes on the pressure surface.

The present study is concerned with the evaluation of adiabatic effectiveness of the film cooling configurations provided on the first stage nozzle guide vane of a modern gas turbine engine provided with film cooling configurations on two locations on suction surface and two locations on the pressure surface. At each location two rows of film cooling holes were provided. The experiments were carried out in a cascade tunnel simulating the design Reynolds number based on blade chord and exit velocity.

2. EXPERIMENTAL FACILITY

Experiments were conducted in a 2-D cascade tunnel with three bladed cascade. Details of the cascade tunnel are in Ref.4. The cascade exit was to atmosphere. The central blade was provided with film cooling holes and was instrumented to measure the film cooling effectiveness. A separate line was drawn for the secondary flow with a pressure regulator, orifice plate for measuring mass flow and heating / cooling system. The required blowing ratio was established by setting the mass flow through the cooling holes (by setting the coolant pressure in the chamber, provided in the blade for the respective cooling hole rows). The first series of film cooling experiments were carried out with secondary flow at higher temperature and the main stream at room temperature. The coolant was heated to the required temperature by air heating system. The coolant temperature was measured by means of thermocouples provided in the coolant inlet chamber provided in the blade. In these experiments, the coolant temperature was around 10°C higher than the mainstream resulting in coolant to mainstream density ratio of around 0.97. The second series of experiments were carried out simulating density ratios higher than unity. A small heat exchanger was fabricated for cooling the secondary flow. Both dry ice (solid CO_2) and liquid nitrogen were used as cooling medium to achieve density ratios 1.2 and 1.56 respectively. The desired mainstream flow condition was set by measuring the total pressure at the inlet to the cascade. The experiments were conducted at Reynolds number = 0.67×10^5 based on blade chord and exit flow condition. The free stream temperature was measured by means of a thermocouple fixed at the cascade inlet. The turbulence level in the region one chord upstream of the cascade inlet was measured by means of a DISA hot film anemometer. The minimum turbulence intensity in the tunnel was 3 %.

3. AIRFOIL AND FILM COOLING CONFIGURATIONS

The first stage nozzle guide vane profile of a modern Gas Turbine engine was selected for the study. A four times scaled up geometry was used. The chord of the model was 320 mm. The hollow vane was fabricated using casting araldite, which has low thermal conductivity (Fig.1). The vane inner profile corresponded to the actual vane inner profile except near the trailing edge region. The wall thickness was of the order of 4.5 mm. The trailing edge region, due to small thickness, was cast as a solid piece. The vane was provided with four pairs of film cooling hole rows, two on the suction surface (SS1 and SS2), two on the pressure surface(PS1 and PS2). The cascade parameter details of film cooling hole geometry provided on the suction and pressure surfaces are listed in Table-1. In the inner surface a partition was made resulting in two chambers for supplying the secondary air to film cooling holes. Each chamber supplied the secondary air to one pair of row on suction surface and one pair of row on pressure surface. A static pressure tapping was provided to measure the pressure in each chamber. In addition, static pressure tapings were provided on the vane surface at the location of the film-cooling holes to measure the local static pressure on the vane profile and was used for estimating the local velocity and density. Fig.3 shows the schematic of the film cooling hole configurations. The film cooling holes were fabricated using rapid prototyping technique. Rectangular slots were provided in the blade at appropriate locations. Rectangular inserts were fabricated with film cooling holes and the inserts were located in the respective slots provided in the blade and adhered to the blade by means of adhesive araldite. Subsequently the blade surface was finished to ensure uniform surface without local discontinuity. Downstream of each pair of film cooling holes insert a thin stainless steel sheet (0.1 mm thickness) was adhered to the blade surface with adhesive araldite. A total of 80 thermocouples were soldered to the sheet to measure local surface temperature. The thermocouples were arranged in a number of rows in the flow direction. In each row, a number of thermocouples were arranged in the pitchwise direction to measure the adiabatic effectiveness variation in the pitchwise direction. The stainless steel sheet was so positioned that it followed the contour of the airfoil surface. The low thermal conductivity araldite substrate and small thickness of the stainless steel sheet ensured that thermocouples measure the local adiabatic temperature on the blade surface.

4. EXPERIMENTAL CONDITION

In the present study, detailed experiments were carried out to obtain the adiabatic film cooling effectiveness distribution downstream of the film cooling configurations provided on the suction and pressure surfaces. Initial experiments were conducted with mainstream at room temperature and the secondary fluid at a temperature around 10°C above the main stream. The coolant to mainstream density ratio was approximately 0.97. The pitchwise average adiabatic cooling effectiveness (η) over one pitch was estimated using the relation:

$$\eta = \frac{(Taw - T\alpha)}{(Tc - T\alpha)} \tag{1}$$

Where Taw is the pitchwise average adiabatic wall temperature, Tc is the coolant temperature and $T\alpha$ is the free stream temperature. The first series of experiments were concerned with the evaluation of the cooling effectiveness distribution downstream of each pair of cooling hole configurations independently with coolant at a higher temperature than the mainstream. The second series of experiments were concerned with investigation on the effect of coolant to mainstream density ratio on the adiabatic film cooling effectiveness distribution downstream of film cooling holes with the secondary flow cooled below the mainstream temperature in a heat exchanger. The third series of experiments were concerned with the evaluation of the combined effect of the film cooling holes provided on suction and pressure surfaces

5. RESULTS AND DISCUSSION

5.1 Film cooling effectiveness distribution at density ratio = 0.97

The first series of experiments were carried out with hot secondary flow with the coolant to mainstream density ratio equal to 0.97. The adiabatic film effectiveness downstream of each row of holes was measured over a range of blowing ratio 0.35 to 2.5 establishing flow through each pair of row independently. Fig.2 shows the adiabatic film cooling effectiveness downstream of PS1 row as a function of blowing ratio. Similar behavior was observed downstream of PS2 row. The results indicate that on the pressure surface the blowing ratio has negligible effect on the effectiveness distribution. The effectiveness decays rapidly and the effect of first row does not extend in the region downstream of the second row. Fig.3 shows the adiabatic film cooling effectiveness downstream of SS1 row as a function of blowing ratio. Similar behavior was observed downstream of SS2 row. In the case of suction surface, the effectiveness in the region downstream of the hole initially remains constant over a significant distance and starts reducing gradually. The effect of the injection through the first row of holes extend in the region downstream of the second row also. The effectiveness exhibited small dependence on the blowing ratio. As the film cooling configurations provided on the suction and pressure surfaces were similar, their performances were compared (Fig.4). The results indicate that the magnitude of the adiabatic effectiveness was lower and the decay of adiabatic effectiveness faster on the pressure surface in comparison to those on the suction surface indicating the effect of surface radius of curvature. Due to faster decay of film cooling effectiveness, the coverage produced by film cooling on the pressure surface was much lower.

5.2 Effect of density ratio on film cooling effectiveness distribution

The second series of experiments were carried out setting the coolant to mainstream density ratio equal to 1.2 and 1.57. The effect of coolant to main stream density ratio on the film cooling performance was evaluated only for the film cooling configurations provided on the suction surface. To identify the effect of coolant to mainstream density ratio on the effectiveness distribution, the data generated at different density ratios but at same blowing ratios are compared (Fig.5). In the region immediately downstream of the film cooling holes, a small increase in the magnitude of effectiveness was observed with increase in coolant to mainstream density ratio. At higher coolant to mainstream density ratio the film effectiveness decays faster and at larger downstream distances the magnitude was lower than that for lower coolant to mainstream density ratio. The results suggest that the film effectiveness data obtained with coolant to mainstream density ratio equal to 0.97 with heated secondary air would be conservative.

5.3 Estimation of additive effect of film cooling effectiveness distribution

A series of experiments were carried out to identify the additive effect of the two rows on both suction and pressure surface. The measurements were carried out in the region downstream of the second row of holes, PS2 and SS2 respectively. Fig.6 shows the effectiveness distribution when the blowing ratios for the two rows SS1 and SS2 are 0.69, 0.79. In the case of suction surface, in the region downstream of the second row of holes the effectiveness value measured with flow through both the rows of holes was higher than that measured for flow through the second row alone at that blowing ratio. Using the correlation for estimating the additive effect of multirow holes, the effectiveness in the region downstream of the second row were calculated using the relation:

$$\eta_{aw} = \eta_{aw1} + (1 - \eta_{aw1}) * \eta_{aw2} \qquad (2)$$

where η_{aw1} is the adiabatic effectiveness at the selected location due to upstream row (SS1) and η_{aw2} is that due to second row (SS2). The results indicate that in the case of flow through both the hole rows the effectiveness distribution downstream of the second row can be estimated with satisfactory accuracy using the above correlation.

6. CONCLUSIONS

Detailed experiments were carried out in a cascade tunnel at design Reynolds number using scaled up profile to obtain the film cooling effectiveness distribution downstream of film cooling holes provided on the suction and pressure surface of a modern nozzle guide vane. The nozzle guide vane was provided with film cooling configurations on two locations on suction surface and two locations on the pressure surface. At each location two rows of film cooling holes were provided. Experiments were carried out varying the blowing ratio in the range of 0.35 to 2.5 and coolant to main stream density ratio in the range of 0.97 to 1.57. The results indicate that the magnitude of the adiabatic effectiveness was lower and the decay of adiabatic effectiveness faster on the pressure surface in comparison to those on the suction surface indicating the effect of surface radius of curvature. The film cooling effectiveness data obtained on the suction surface indicate that at higher coolant to mainstream density ratio the film effectiveness decays faster and at larger downstream distances the magnitude was lower than that for lower coolant to mainstream density ratio. The results also indicate that on the suction surface in the case of flow through both the hole rows the effectiveness distribution downstream of the second row can be estimated with satisfactory accuracy using the correlation for additive effect of film cooling.

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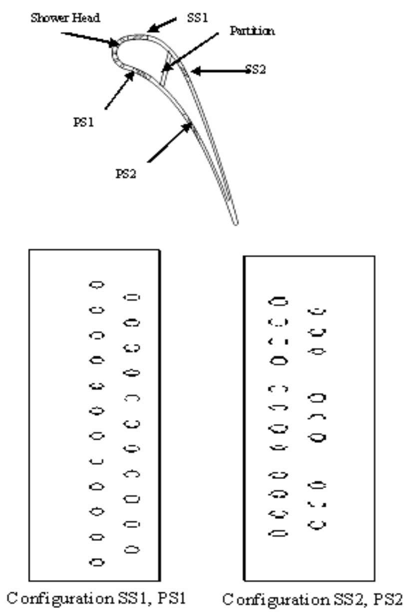

Fig 1. Details of Test Model

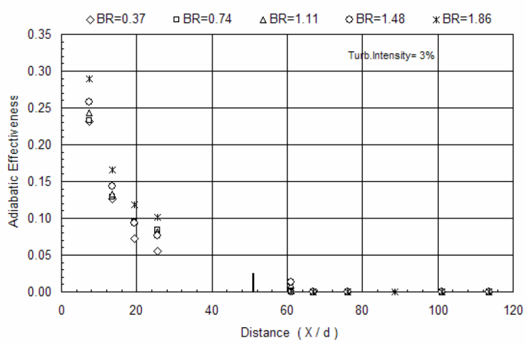

Fig.2 Adiabatic film cooling effectiveness variation with X / d - Pressure surface - injection through film cooling row PS1

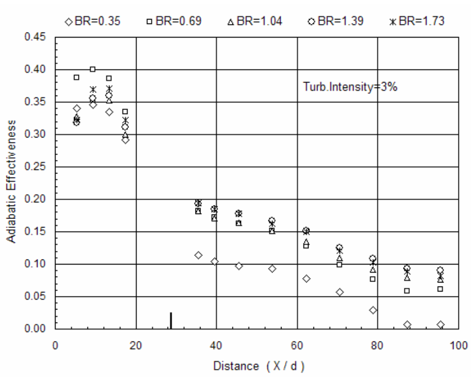

Fig.3 Adiabatic film cooling effectiveness variation with X / d - Suction surface - injection through film cooling row SS1

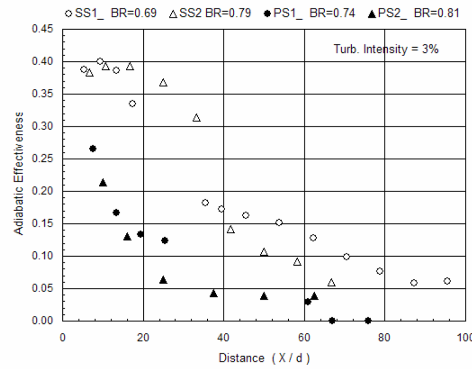

Fig.4 Comparison of adiabatic film cooling effectiveness variation with X / d on Pressure surface and suction surfaces

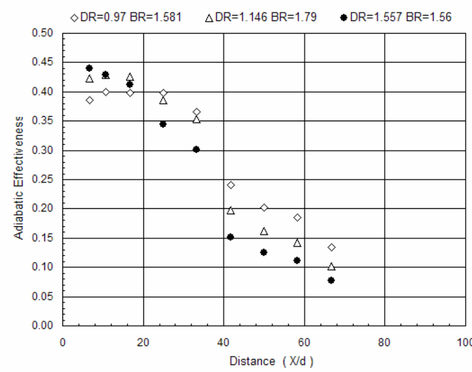

Fig.5 Adiabatic film cooling effectiveness variation with distance(X/d) Suction surface - Effect of density ratio - injection through film cooling row SS2

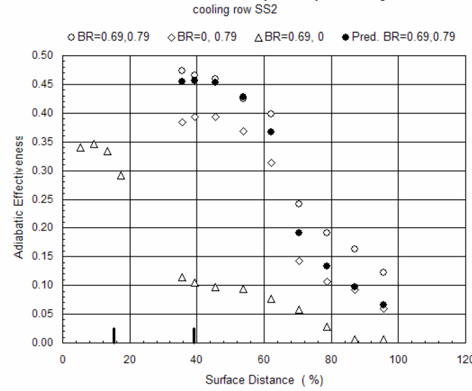

Fig. 6 Adiabatic film cooling effectiveness variation with surface distance Suction surface - injection through film cooling rows SS1 and SS2

Table 1: Cascade Parameters and Film cooling Geometry:

Cascade Parameters:

Pitch/Chord	0.711
Stagger Angle(Deg)	56
Incidence Angle	0

Film Cooling Geometry:

	PS1	PS2	SS1	SS2
Hole Angle	35	20	45	35
Pitch/Hole Dia	4	3.2	4	3.2