

文章编号: 1000-8055(2010)05-1097-06

Experimental investigation of aerodynamics of turbine blade trailing edge cooling

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Abstract: This paper presented an experimental investigation the effects of the trailing edge cooling on the aerodynamic performance. The experiments were conducted on the low-speed linear cascade tunnel at Northwestern Polytechnical University. The external aerodynamic characteristics in the 40 percent chord downstream of exit plane were measured using five hole probe with the different ejection rates. The results showed that the total pressure loss coefficient at the middle spanwise plane increased at first and then it has a decreasing tendency with the increase of ejection ratio. The trailing edge cooling would influence the structure of the turbine cascade outlet flow field. When the ejection rate was 3%, the loss area near the blade endwall would become stronger, but it would become weaker with the 6% ejection ratio. On the whole, the trailing edge cooling had more influence on the profile loss than on the secondary loss.

Key words: turbine blade; trailing edge cooling; profile loss; secondary loss

CLC number: V231.3

Document code: A

Introduction

In order to increase the specific thrust and to reduce the specific fuel consumption of gas turbine engines, higher turbine inlet temperatures are needed. This need for high temperatures results in a demand for effective cooling of high-pressure turbine blades. Many of the blade cooling systems involve ejection of cooling flows into the hot gas stream at various points on the blade. One of the most critical locations on the blade where coolant ejection is performed is the trailing edge. The mixing of coolant with main stream gases can result in aerodynamic losses, which will influence the engine performance.

Aerodynamic aspects associated with edge coolant ejection in steady two-dimensional blade-to-blade flow over a range of exit Mach numbers

and coolant pressure ratios were studied by Deckers and Denton^[1]. It was concluded that the effect of coolant ejection is a substantial increase in the base pressure and a reduction in overall loss. Pappu and Schoeiri^[2] investigated the aerodynamic effects of trailing edge ejection on mixing losses downstream of cooled gas turbine blades. The results indicate that for an ejection velocity ratio of unity, the trailing edge ejection reduces the mixing losses. An investigation of the flow field downstream of a turbine trailing edge cooled nozzle guide vane is described in Sieverding et al^[3]. A cutback trailing edge ejection system discharging on the pressure side of the blade is used. It was concluded that the coolant flow ejection did not produce any unusual wake flow patterns in the measurement planes. This feature was explained with very rapid mix-

ing of coolant with mainstream flow. Mee^[4] discussed the experimental methods required to compare different trailing edge region coolant ejection geometries. It is suggested that if the additional complexity associated with foreign gas ejection or cooled air injection is to be avoided. The external aerodynamic loss characteristics were measured using PIV and total pressure probe by Uzol et al^[5]. The results show that there is a ejection ratio with that the external aerodynamic loss is greatest. SUN Dawei and QIAO Weiyang^[6] investigated the two different trailing edge cooling with numerical simulation and experiment. It was concluded that aerodynamic performance of pressure side cutback cooling is better than the symmetry slot coolant ejection. Other researchers^[7-12] have also done a lot of research work.

The downstream flow field of a linear turbine blade is investigated with several ejection ratios on this study. The main objectives of this paper are to study the influence of different ejection ratios on the aerodynamic characteristics of external flow field and to try to get a significantly conclusion which would help to the turbine cooling designer.

1 Experimental facilities

The present investigations were carried out in the low speed turbine cascade wind tunnel of Northwestern Polytechnological University. The wind tunnel is powered by a 18kW motor with a fan. This then proceeds to a diffuser, a settling chamber, a series of flow conditioning screens, a contraction and then into the test section as shown in Fig. 1.

The test section consists of two parallel end plates, aligned horizontally, between which a cascade with 7 blades is installed. The middle blade is instrumented to simulate trailing edge coolant ejection. The inlet section has a regular cross section perpendicular to the flow direction, with dimensions of 300mm × 90mm.

A traverse system was built specifically for this cascade tunnel. The traverse consisted of a

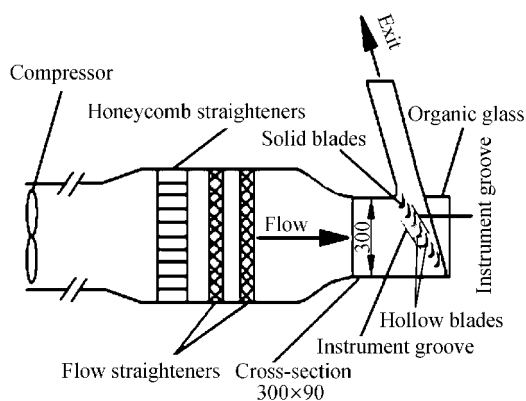


Fig. 1 Low speed linear cascade tunnel at Northwestern Polytechnical University

three-axis movement system. Movement of each axis is controlled by individual stepper motors which are controlled through a personal computer (PC). The inlet total pressure was measured using a total pressure probe. The Traverse measurements in the 40 percent chord downstream of the cascade exit plane with a five-hole probe are conducted with different ejection ratios. The five-hole probe with external size of 2.6 mm was mounted on three-axis coordinate movement system. The probe was fixed to the upper wall of the cascade and was inserted into the flow field. The probe was calibrated in a probe calibration wind tunnel. The accuracies of the measured total pressure and velocity are 0.01 percent of the inlet midspan values from where all the reference parameters were taken. The uncertainty of the measured flow direction was better than 1 deg. The total number of measurement points was 630 (15 spanwise × 42 pitchwise locations).

The turbine blades have a chord length of 0.0646m, which gives a pitch to chord ratio of 0.725 and a span to chord ratio of 1.39. The blades are placed with a 42.5 deg stagger angle with an inlet flow angle of 0 deg and an exit flow angle of 65.1 deg. The width of trailing edge coolant slot is 1mm. The structure of the blade are showed in Fig. 2.

In this test the Mach number based on the was 0.092 and the Reynolds number based on the true chord length and exit velocity was 1.117×10^5 . The freestream turbulence intensity

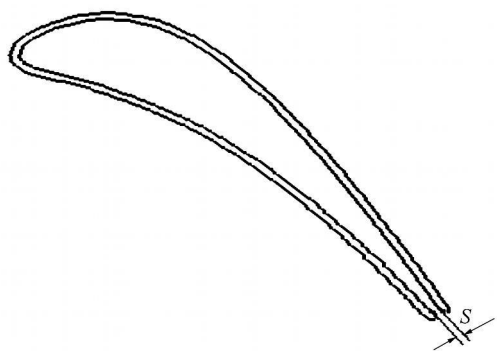


Fig. 2 Schematic of blade with cooled ejection slot

was less than 1%. The coolant is supplied by an compressor from the air. So the coolant has the same characteristics as the freestream.

2 Results and discussion

The total pressure loss coefficient is defined as:

$$\phi = \frac{p_{10} - p_{11}}{\frac{1}{2}\rho u^2}$$

Where p_{10} represents the inlet total pressure and p_{11} represents the local total pressure. $\frac{1}{2}\rho u^2$ is the dynamic pressure of the external flow plane.

2.1 Measurement result at midspan plane

First a total pressure traverse at midspan of the middle blade is performed independently using a five-hole probe with eight ejection ratios. The result is illustrated in Fig. 3.

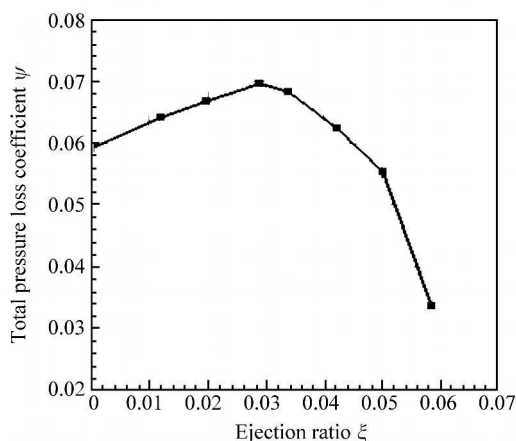


Fig. 3 Curve of ejection ratio to total pressure loss coefficient at mid spanwise plane

As shown in Fig. 3, when the ejection ratio is low, the total pressure loss coefficient increases at first and then it has a decreasing tendency with the increase of ejection ratio. The point where the total pressure loss coefficient is largest is the state with the 2.9% ejection ratio. With the higher ejection ratio, the total pressure loss coefficient decreases swiftly with the increase of ejection ratio.

In order to know more about the influence of coolant jet on the external aerodynamic characteristics, the total pressure loss distribution of external wake is shown in Fig. 4.

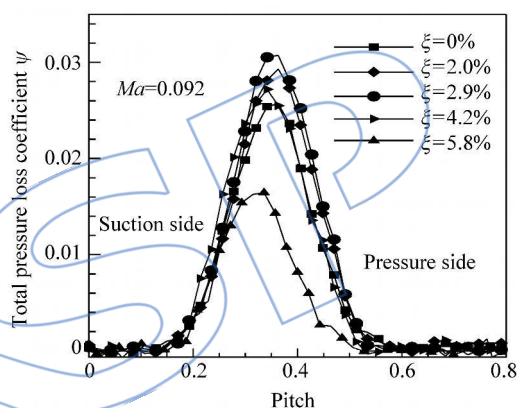


Fig. 4 Exit wakes at mid spanwise plane with coolant ejection

Fig. 4 shows that the loss top and width of the wake become large with the increase of ejection ratio under the condition of low ejection ratio. When the ejection ratio is 2.9%, the loss top of the wake reaches the biggest point. And then the loss top increases continually with the increase of ejection ratio, the width of the wake becomes short evidently. The wakes move to the suction side of the blade comparing with the wake without cooling jet.

The reason of the change of the external aerodynamic loss characteristics with coolant ejection at midspan plane was explained in literature [6]. The midspan plane of turbine cascade is not almost influenced by the secondary flow. So the rule of the change of the total loss pressure with coolant ejection at the midspan is the same as the change of profile loss.

2.2 Measurement result of the out flow field

The flow field at the exit of the turbine blade were also investigated. with three ejection ratios. The three ejection ratios which are decided based on Fig. 3 are 0%, 3.0% and 6.0%. Because the turbine cascades in the test are linear cascade, the structures of the upside and down side flow field are similar. Only the half flow field was measured. Fig. 5, Fig. 6 and Fig. 7 show the distribution of total pressure loss with the three ejection ratios. As the total pressure loss contours show, when the ejection ratio is 0%, the flow field is not influenced by the coolant and the shape of wake is straight. The higher loss region which are near the endwall and at the 20% spanwise height are obvious because of the secondary flow. The core locates at 13% spanwise height. When the ejection ratio increases to 3.0%, the wake moves to the suction side and turns to curve. The shape of the wake looks like "C". The loss of the wake become larger. Especially, in the endwall region with higher loss, the loss intensity and area of this region become strong obviously. The core moves to the 10% spanwise point. For 6.0% ejection ratio, the flow field is influenced by the high speed cooling gas, the wake moves to the suction side evidently. The shape of the wake become more curving and the "C" distribution is more visible. Comparing with the wake for the 0% ejection ratio, the width becomes shorter and the loss intensity and area of the high loss region near the endwall become weaker. The core moves up to 12% spanwise height.

The spanwise distribution of the total pressure loss with three ejection ratios can be seen in Fig. 8. The total pressure loss coefficients with the 3.0% ejection ratio are the most of the three states and the loss coefficients for the 6.0% ejection ratio are the least of all. Between the 50% and 20% along spanwise height, the difference of the loss coefficients for the three ejection ratio are almost changeless. The reason for the invariability of the loss maybe that the total loss is

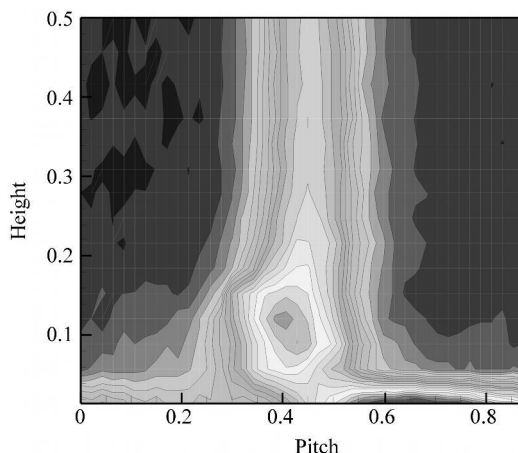


Fig. 5 Total pressure loss contour with 0% ejection ratio

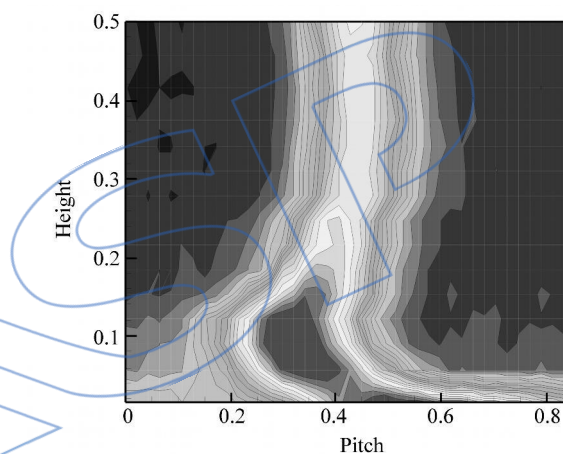


Fig. 6 Total pressure loss contour with 3.0% ejection ratio

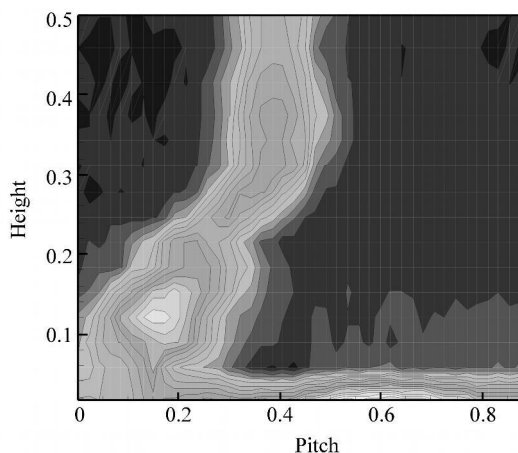


Fig. 7 Total pressure loss contour with 6.0% ejection ratio

mostly influenced by the profile loss which be determined by the ejection ratio in the test and

the effect of secondary flow is weak in this region. But in the endwall region which be mostly influenced by secondary flow (below 20% spanwise height), the change of the total pressure loss coefficients are different evidently. The difference of total pressure loss between the three ejection ratio mean that the trailing edge coolant ejection would influence the outlet secondary flow.

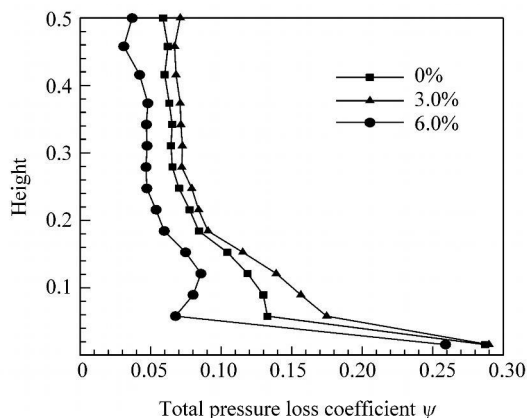


Fig.8 Average total pressure loss coefficient distribution along spanwise height

In order to study the influence of the trailing edge coolant ejection on the different kinds of the aerodynamic loss at the exit, the total loss is divided into profile loss and secondary loss. The average of the total pressure loss coefficients on the three planes near midspan is considered as the profile loss of the blade. Then the profile loss subtract from the total loss gives the secondary loss. Fig. 9 shows the different kinds of the

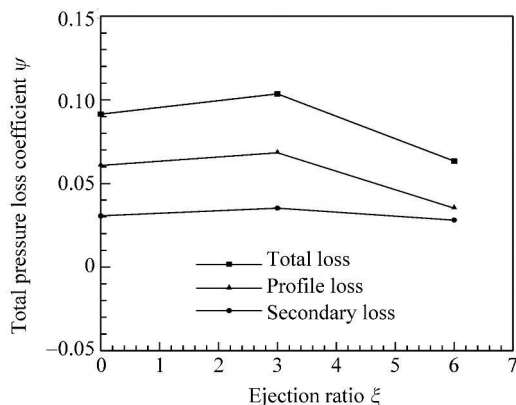


Fig.9 Curve of ejection ratio to total loss, profile loss and secondary loss

aerodynamic loss for the three ejection ratio.

As shown in Fig. 9, the total loss and the profile loss have the same changing tendency, they increase at first and then decrease with the increase of ejection ratio. The secondary loss has the similar changing tendency, but the range of the loss changing is not extensive.

3 Conclusions

Experiments on a linear turbine cascade are performed to study the influence of trailing edge coolant ejection on aerodynamic loss characteristics in this paper. The results show that:

1) At the midspan plane of blade, the total pressure loss increases at first and then it has a decreasing tendency with the increase of ejection ratio for the low ejection ratios. And for the high ejection ratio, the total pressure loss decreases swiftly with the increase of ejection ratio. In all cases the calculated results exhibit fair agreement with experiment data. The wakes move to the suction side of the blade comparing with the wake without cooling jet.

2) Trailing edge coolant ejection can produce the heavy influence on the structure of the outlet flow field. With the increase of ejection ratio the wake moves to the suction side, and the wake becomes more incurved.

3) The outlet secondary flow structure can be influenced obviously by the trailing edge coolant ejection. Comparing with the state without coolant ejection, the intensity of the secondary flow turns to strong evidently for the 3.0% ejection ratio, the intensity become weak for the 6.0% ejection ratio.

4) The profile loss and secondary loss would increase at first and then decrease with the increase of ejection ratio. But the changing range of the secondary loss is smaller evidently than the profile loss.

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