

Experimental Investigation of Boundary Layer Characteristics on Blade Surface under Different Inlet Flow Conditions

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Abstract

In this paper, an experimental study is conducted on cascade boundary layer under different inlet conditions. New method is used to measure the total pressure in blade surface boundary layer directly using total pressure probe. Total pressure in both suction and pressure surfaces are acquired at different inlet conditions by changing incidence angle and inlet Mach number. In addition, a series of parameters related to boundary layer characteristics are calculated. The objective of the experiment is to investigate the influence of inlet flow conditions on them. The results indicate that influence of incidence angle is significant when other conditions are the same. Displacement thickness, momentum thickness as well as other parameters display some disciplines for variation. In contrast, inlet Mach number has only a small influence in that boundary layer becomes a litter thinner with increasing Mach number. Comparisons of experimental results with theoretical expectations demonstrate that the method in this experiment is effective and reliable.

Keywords: Boundary Layer, Cascade, Inlet Flow Conditions, Total Pressure Probe

1. Introduction

Modern developing trend for aero-engine is toward high performance, wide range of work, high efficiency and high thrust-to-weight ratio [1-3]. Compressor is a key component of aero-engine which holds a large share in size and weight. Therefore, improving the performance of fan and compressor plays a vital role [4].

End-wall boundary layer, blade surface boundary layer and their interaction lead to great flow loss. Inlet flow conditions have an important impact for boundary layer on its development, separation and transition [5-6]. Along history, wind tunnel experiment is always an important method for research. In early times only inlet or outlet flow parameters are directly measured. This method does no help to understand the specific loss mechanism in cascade. With the variation of research emphasis, the whole flow conditions in cascade need to be investigated. Many scholars have already conducted such experiments and provided some valuable results [7-9].

In this paper, an experimental research on both suction

and pressure surface boundary layer is conducted on high subsonic cascade wind tunnel. The impacts of different inlet flow conditions on boundary layer characteristics are discussed in-depth. Experimental investigation is conducted to get detailed information about the velocity, displacement thickness and momentum thickness of boundary layer.

2. Design of Experiment and Experimental Devices

2.1. Design of Experiment

Total pressure in boundary layer on both suction and pressure surface is measured using total pressure probe. The cascade wind tunnel is composed of gas source, regulator section, convergence section, experimental section, end wall boundary layer suction devices and control system. The wind tunnel structure is showed in **Figure 1**. Parameters of the tested cascade are in **Table 1**.

The total pressure probe can only measure one posi-

Table 1. Parameters of tested cascade.

Chord length	65 mm
Cascade pitch	43.92 mm
Inlet geometry angle	42°
Outlet geometry angle	78°
Stagger angle	27°

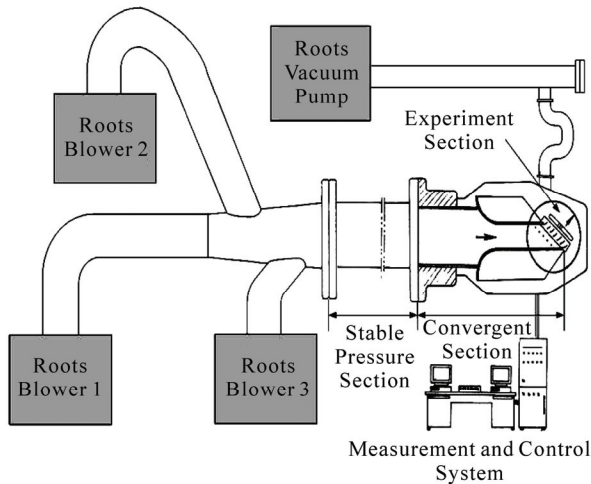


Figure 1. Sketch of cascade wind-tunnel.

tion each time and a large number of measuring points must be selected. Measuring points are selected according to practical requirements and experimental conditions [10-11]. In order to understand the characteristics of boundary layer along the entire blade surface, measuring points are selected from leading edge to trailing edge at a distance of 10% of chord length, which is shown in **Figure 2**. Limited by the size of experimental device, finally five measuring points are selected on suction surface from 50% to 90% of the chord length, while 7 points are chosen on pressure side from 10% to 70% chord length. The cascade is linear so the air flow is similar along the blade height. In this experiment measuring points are chosen at 40% blade height. In order to measure the thickness of boundary layer, pressure probe has to move along the blade surface vertically. The moving step is 0.1 mm each time.

2.2. Design of Total Pressure Probe

As shown in **Figure 3**, total pressure probe is installed in position 1. Component 4 can revolve on component 6 so that component 2 can move along the vertical direction on blade surface. 3 is a rivet which can fix component 2. Bolt 5 is supposed to fix 4. The whole device is installed in the groove of cascade. During the experiment total

pressure probe is adjusted along the vertical direction of blade surface. The first measuring position is determined where probe touches the blade surface but does not have elastic deformation. In order to ensure the accuracy of probe moving, micrometer is used to determine the exact location.

The total pressure probes are shown in **Figure 4**. Different probes are used to measure the boundary layer on suction and pressure surfaces respectively. Please notice that there is a turn of 3° at position 3 because the probe needs some bending when it is close to blade surface. Total pressure probes are calibrated in calibration wind tunnel of Northwestern Polytechnical University with an accuracy of 0.1 to ensure the accuracy of experiment.

3. Results and Discussion

Flow parameters in boundary layer are measured under

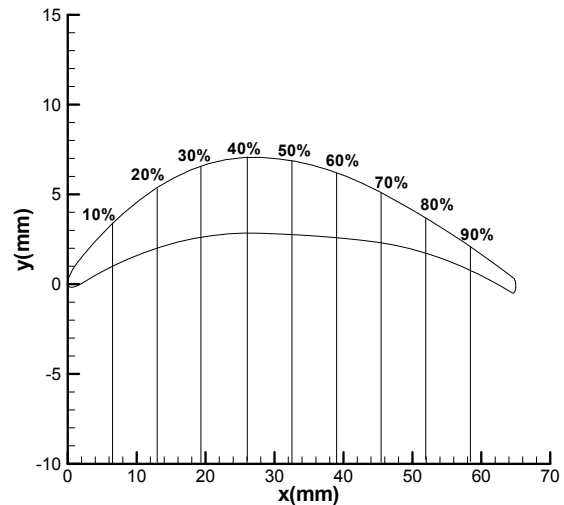


Figure 2. Sketch of measuring positions on blade surface.

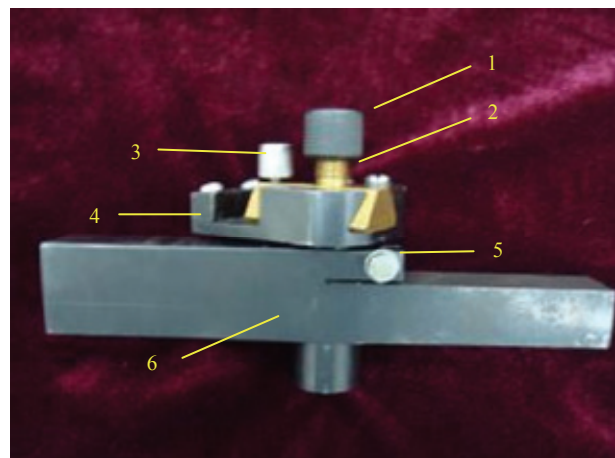


Figure 3. Pressure probe installation device.

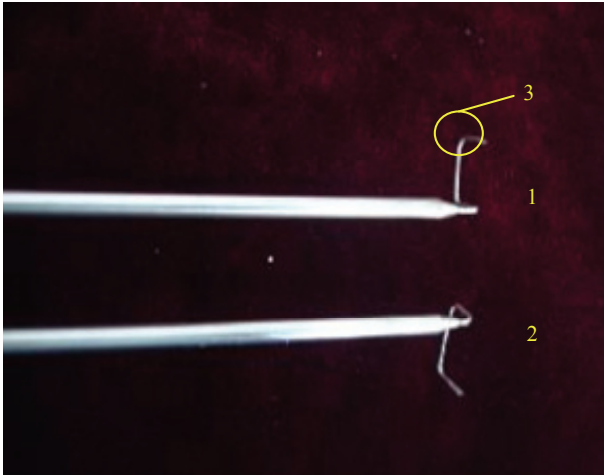


Figure 4. Pressure probe. 1-pressure surface; 2-suction surface.

different inlet conditions. Inlet Mach numbers are 0.60, 0.66 and 0.71 while incidence angles are 0° , 4° and -4° respectively. Displacement thickness, shape factor and momentum thickness were calculated in order to further research the characteristics of boundary layer. Related equations are as follows:

$$\delta_1 = \int_0^\delta \left(1 - \frac{u}{U_e}\right) dz$$

$$\theta = \int_0^\delta \frac{u}{U_e} \left(1 - \frac{u}{U_e}\right) dz$$

$$H = \frac{\delta_1}{\theta}$$

3.1. Effects of Flow Conditions on Pressure Side Boundary Layer

Figure 5 shows the displacement thickness, shape factor and momentum thickness distribution on pressure side under different inlet conditions. It can be seen from **Figure 5(a)** that the displacement thickness changes obviously when the incidence changes. Under 0° incidence the displacement thickness gradually increases when measuring point moves toward trailing edge. Under 4° and -4° incidence, the displacement thickness shows a downward trend after the first rise but finally rises again. It can also be found that there is a slight decline in displacement thickness when inlet Mach number rises. **Figure 5(b)** displays the momentum thickness and shape factor on pressure side. Although momentum thickness has some variations, shape factor is small and almost maintains the same value along the chord under the three different inlet conditions. Thus a conclusion can be

drawn that there is no obvious boundary layer separation on pressure surface under the inlet conditions that are tested.

3.2. Effects of Inlet Flow Conditions on Suction Side Boundary Layer

Figure 6 shows the boundary layer displacement thickness and shape factor on suction side under different inlet flow conditions. It can be seen from **Figure 6(a)** that the influence of incidence on displacement thickness of boundary layer is significant. Generally the displacement thickness has a trend of growth when measuring point moves toward trailing edge. On the other hand, it can be seen that the change of displacement thickness under different Mach number is much smaller. However, the figure does suggest that there is a slight decline in displacement thickness when inlet Mach number is increasing.

Figure 6(b) is the shape factor and momentum thickness of suction surface boundary layer under different incidences. Shape factor is an important parameter which suggests whether the flow is laminar or turbulence and whether the boundary layer has separated. Shape factor of laminar flow is larger than that of turbulence and according to engineering experience, laminar flow begins to separate when shape factor grows to 3.5 or larger while turbulence boundary layer starts to separate when it is larger than 2.2. As shown in these figures, the flow has already turns into turbulence at 50% chord since the shape factor is around 1.5 at that position. Under 0° incidence, turbulent flow becomes instable at the position about 70% chord length and boundary layer may start to separate at 85% chord length. Under 4° incidence, there is a sharp increase in shape factor at about 70% chord length which may indicate a boundary layer separation. When the incidence is -4° , boundary layer separation may not happen on suction surface as the shape factor maintains a low value all the time.

3.3. Effects of incidence angle on flow velocities in the boundary layer

Since inlet Mach number in the test has only a small influence on boundary layer characteristics as demonstrated before, in this part focus is mainly concentrated on incidence angle. **Figures 7** and **8** display the velocity distribution in boundary layer under different incidences with an inlet Mach number of 0.71. “h” represents the vertical distance away from blade surface and “v” means the velocity. “10%-90%” suggests the position of measuring point from leading edge to trailing edge. **Figure 7** is the velocity distribution on suction side. It is clear that

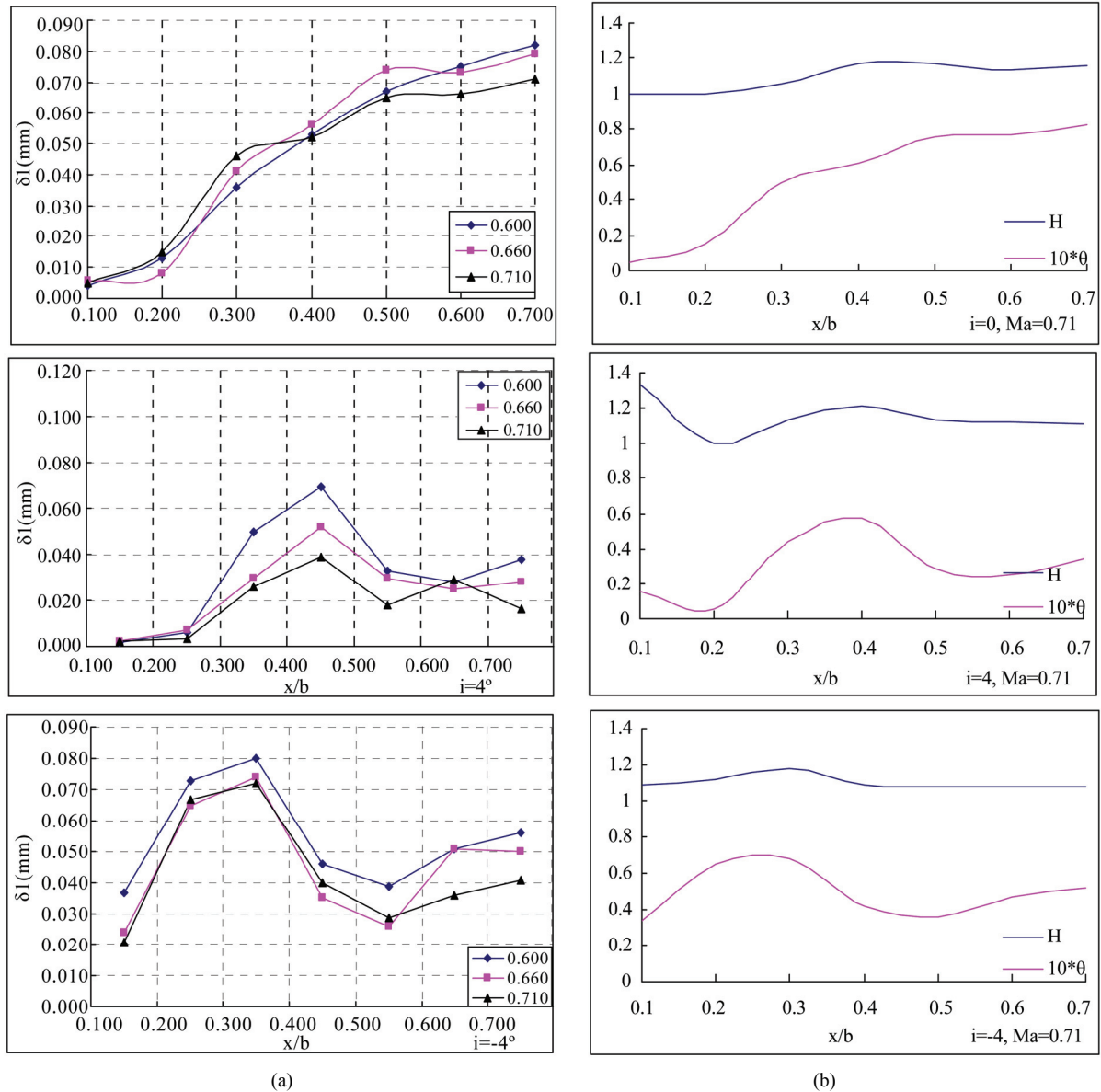


Figure 5. Displacement thickness and shape factor on pressure side. (a) displacement thickness; (b) Shape factor and momentum thickness.

the boundary layer becomes thicker toward trailing edge while the velocity in and out of it has a trend of decline. Under 0° incidence, the boundary layer is 0.5 mm thick at 50% chord length. It increases along the chord and reaches 2.5 mm at 90% chord length. At the same time, the velocity in and out of boundary layer decreases, with the mainstream velocity dropping from 250 m/s at 50% chord to 180 m/s at 90% chord. When the incidence is 4°, the boundary layer evidently becomes thicker along the whole chord than that under 0° incidence. It becomes stable after 70% chord with the value about 2 mm, and the mainstream velocity also turns to be stable with the value about 200m/s. This phenomenon can be caused by

separation on suction surface at about 70% chord as demonstrated in part 3.2. Under -4° incidence, boundary layer thickness has only a slight variation along the chord, almost all 1.2 mm, but mainstream velocity declines gradually toward trailing edge. This agrees well with the conclusion made before that separation may not happen on suction side at negative incidence.

Figure 8 is the velocity distribution in boundary layer on pressure surface. As shown in the figure that incidence angle has a significant influence on boundary layer thickness as well as the flow velocity in it. Unlike the suction side, pressure surface boundary layer has a trend of becoming thicker when incidence angle decreases. It

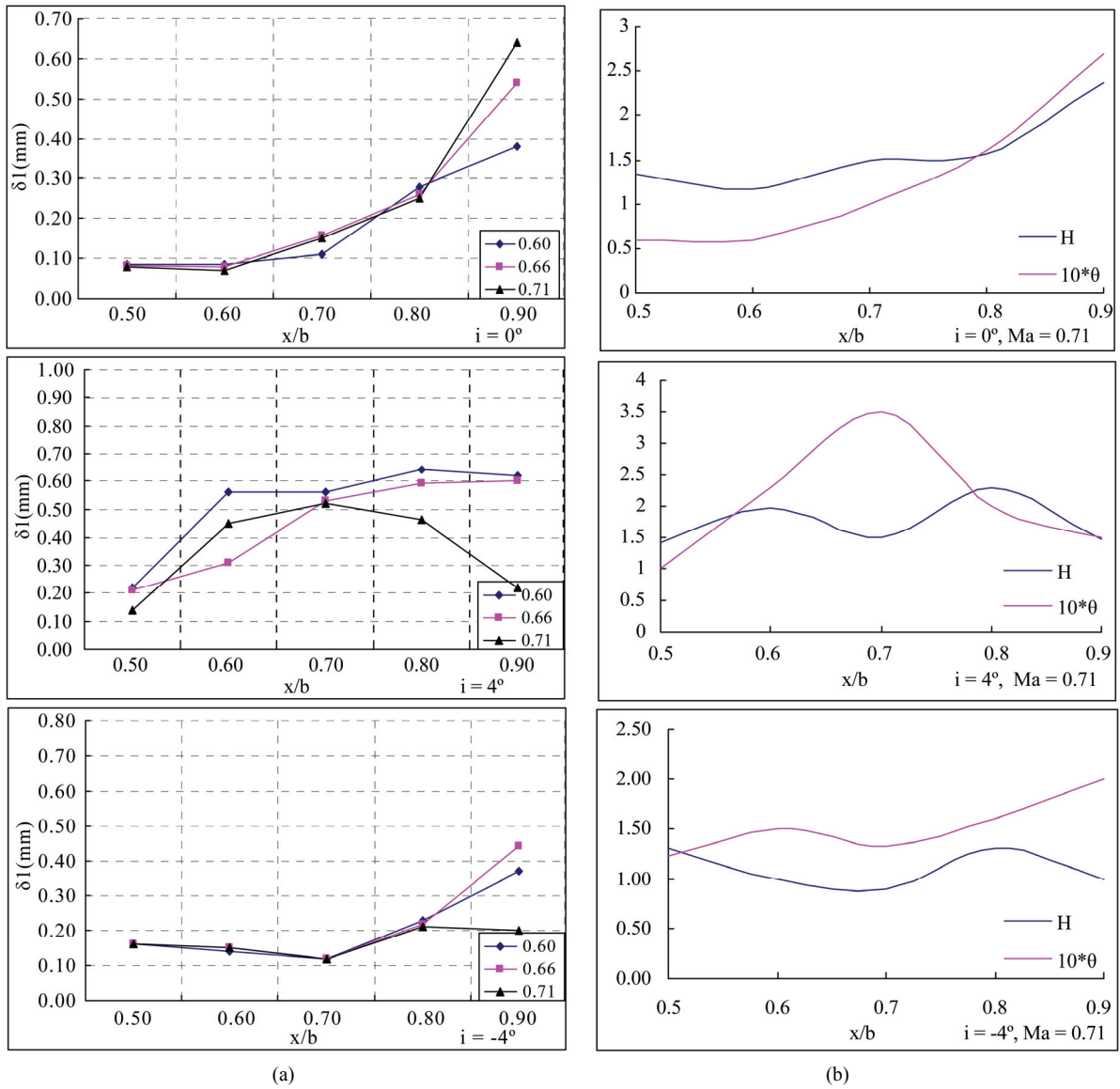


Figure 6. Displacement thickness and shape factor on suction side. (a) displacement thickness; (b) shape factor.

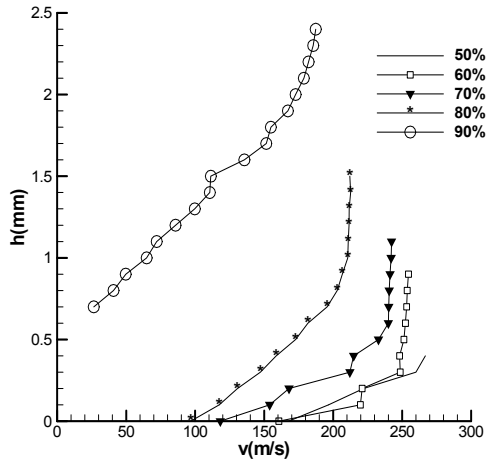
can be seen that when incidence is 4°, the boundary layer is about 0.75 mm thick, it grows to 1.3 mm under 0° and 1.5 mm under -4°. Another phenomenon can be found that boundary layer thickness nearly remains the same along the whole chord when inlet flow conditions are fixed. This demonstrates a conclusion made before that no obvious separation occurs on pressure surface under tested inlet conditions. According to **Figure 8(a)**, under 0° incidence, flow velocity near the wall declines markedly from 205 m/s at 10% chord to 160 m/s at 70% chord when measuring point moves toward outlet. When incidence is 4°, mainstream velocity varies largely along pressure surface with a range of 209 m/s to 188m/s. Under -4°incidence, flow velocity in boundary layer has a varying range from 200 m/s to 165 m/s. Mainstream ve-

locity outside boundary layer has a trend of decline from 215 m/s to 200 m/s.

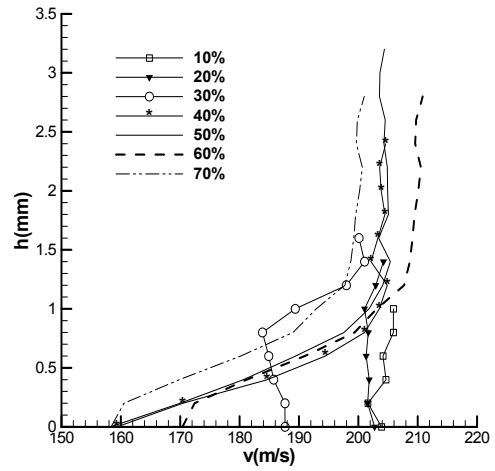
4. Conclusions

1) Inlet Mach number has only a small influence on boundary layer characteristics. At different Mach numbers in the experiment, aerodynamic parameters display almost the same distributions. Nevertheless, displacement thickness does have a little decline when inlet Mach number increases.

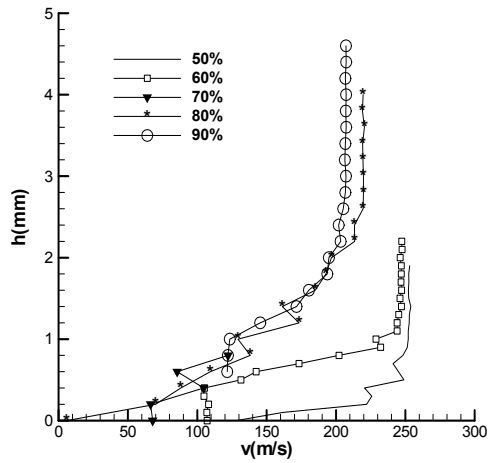
2) Incidence angle has significant influence on boundary layer characteristics compared with Mach number. At different incidences, displacement thickness, momentum thickness and shape factor all show diverse dis-



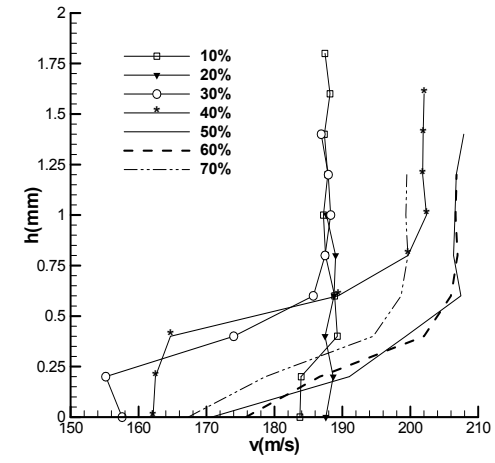
(a)



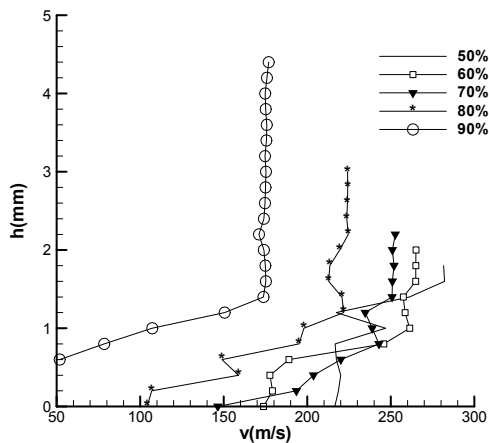
(a)



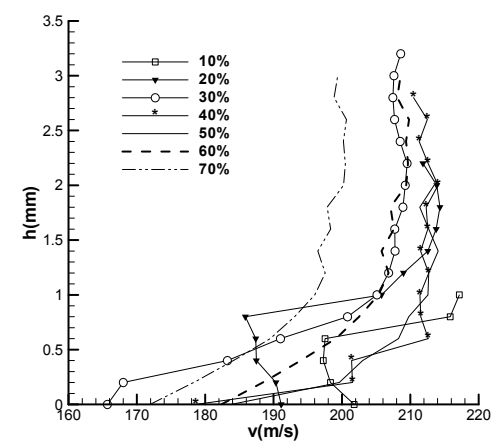
(b)



(b)



(c)



(c)

Figure 7. Velocity distribution in suction side boundary layer. (a) $I = 0^\circ$, $Ma = 0.71$; (b) $I = 4^\circ$, $Ma = 0.71$; (c) $I = -4^\circ$, $Ma = 0.71$.

Figure 8. Velocity distribution in pressure side boundary layer. (a) (a) $I = 0^\circ$, $Ma = 0.71$; (b) $I = 4^\circ$, $Ma = 0.71$; (c) $I = -4^\circ$, $Ma = 0.71$.

tributions on both suction and pressure surfaces. Under negative incidence, no separation occurs on suction or pressure surfaces. With incidence angle rising, separation begins to take place on suction side, and separation happens earlier when incidence angle increases. On the other hand, flow can always maintain on pressure surface without obvious separation at tested conditions.

3) From the influence of incidence angle on flow velocities in boundary layer, on suction surface, under positive incidence boundary layer thickness begins to be stabilized at about 70% chord, which can be caused by separation starting at this position as mentioned in part 3.2. At negative incidence boundary layer thickness is almost the same from inlet to outlet, which further proves that no separation happens; on pressure surface, boundary layer can almost maintain the same thickness along the chord length at all the three incidences, which is also consistent with the shape factor distribution analysed before.

Not only are these experimental results consistent with each other, but they also agree well with theoretical predictions and practical experience thus they can get reasonable explanations. As a result, a conclusion can be safely made that the experimental method used in this paper is effective and reliable. In the future, more in-depth experiments of boundary layer can be conducted using this method.

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Nomenclature

b = chord

Ma = Mach number

u = axial velocity [m/s]

U_e = external axial velocity [m/s]

v = transversal velocity [m/s]

t = cascade pitch

β_{1k} = inlet geometry angle

β_{2k} = outlet geometry angle

β_y = stagger angle

x = axial coordinate [mm]

y = transversal coordinate [mm]

z = vertical coordinate [mm]

h = vertical distance from blade surface [mm]

H = shape factor

i = inlet flow incidence [deg]

δ = boundary layer thickness [mm]

δ_1 = displacement thickness [mm]

θ = momentum thickness [mm]