33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

EXPERIMENTAL INVESTIGATION ON JET IMPINGEMENT HEAT TRANSFER WITH CROSS FLOW FOR AERO-ENGINE INLET CONE

Xinwei Jiang[1], Guochao Liu[1], Jianjun Zhou[1], Qi Jia[1]

[1]AECC Shenyang Engine Research Institute, Shenyang, 110015, China

Abstract

In order to obtain the jet impingement heat transfer characteristics of aero-engine inlet cone, a series of impingement heat transfer experiments were carried out in a curved surface channel using Transient Liquid Crystal (TLC) temperature measurement technique. The effects of jet Reynolds number (*Rej*), cross flow Reynolds number (*Rec*), dimensionless hole space (*p/D*) and impingement distance (*h/D*) on Nusselt number (*Nu*) of the full surface were investigated. The experimental study shows that, the jet Reynolds number has an obvious enhancement effect on the overall Nusselt number. The Nusselt number in the whole region increases obviously when the jet Reynolds number increases gradually. The hole space has a weaker effect on the area between jet holes with the increase of hole space. The Nusselt number at the stagnation point increases significantly due to the addition of cross flow when the impingement distance is 0.5.

Keywords: Jet impingement; Heat transfer; Cross flow; Transient Liquid Crystal

1. Introduction

Icing of aircrafts and engines affects flight safety seriously. At present, hot air anti-icing system is still the main method of engine icing protection, for which hot air is discharged from the compressor to heat the parts to be protected, so that the surface temperature is higher than freezing point of water and avoid the accretion of ice. For aero-engine inlet cones, enhanced heat transfer with jet impingement is usually applied [1]. A computational fluid dynamics method was adopted to study the internal jet impingement heat transfer and external film heating efficiency. Results show that increasing Reynolds number is conducive to improving the internal jet impingement heat transfer and external film heating efficiency [2]. The flow heat transfer characteristics of the leading edge structure of the single-hole impact cone were studied by numerical method [3]. A comparative study is conducted to investigate the heat transfer characteristic of turbulent flow in the hot air anti-icing system with and without surface convex by using numerical simulation method [4]. The numerical simulation algorithm of three dimensional water droplet impingement based on Eulerian-Eulerian method was developed and verified by experimental data from references [5]. Numerical simulation method was carried out to study the influence of the structural parameters on the thermal performance of the hot air anti-icing system [6].A series of experimental studies on icing and de-icing for aircrafts and engines have been carried out in NASA Glenn Research Center [7]-[8]. In addition, a large number of jet impingement heat transfer experiments have been investigated [9].

Based on the analysis of above literatures, In order to obtain the impingement heat transfer characteristics with cross flow for aero-engine inlet cone, impingement heat transfer experiments were carried out in a curved surface channel using transient liquid crystal (TLC) temperature measurement technique. In this paper, the effects of dimensionless hole space, jet Reynolds number, dimensionless impingement distance and cross flow Reynolds number on the Nusselt number distribution of the curved surface were analyzed in detail. The results can help researchers understand the mechanisms and laws of anti-icing by hot air more deeply.

2. Experiment facility & conditions

The experimental system of hole rows structure of cone was shown in Figure1, which was mainly divided into mainstream system and secondary flow system. The compressor supplies air to the experimental section. As the main flow was large and the air pressure from the compressor was unstable, a pressure maintaining valve was added at the inlet of the main flow section. In order to ensure that the air flow entering the experimental section had a uniform initial temperature, four thermocouples were arranged at the entrance of the experimental section to measure the initial temperature of the air flow.

In the experiment, the volume flow was calculated by Reynolds number. The camera was used to record the relationship between the color change of liquid crystal and time, calculate the temperature of the inner surface, and further obtain the heat transfer coefficient of the inner surface of the cone. As shown in Figure 1, an experimental model coated with liquid crystal of curved surface channel was established, and the heat transfer coefficient distribution of the whole surface was measured by TLC temperature measurement technique. The TLC has the following advantages: high accuracy, fast response to temperature variations, suitable for temperature measurement on convective surface, etc.

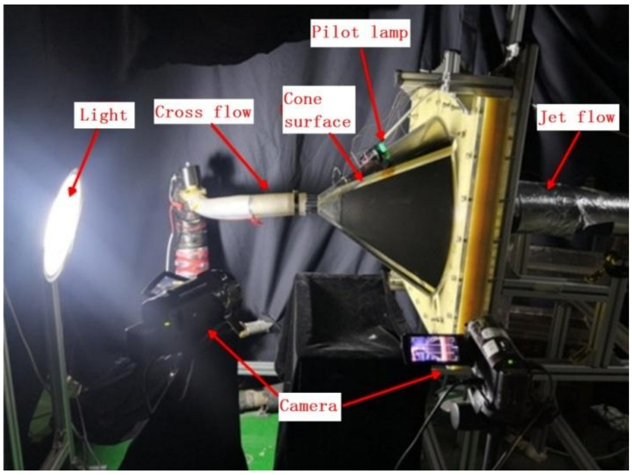


Figure 1.Experimental facility

Figure 2 shows the model of the experimental subject. *D* represents the jet flow diameter, *h* is the jet flow impact distance, and *p* is the hole space of impingement holes. The jet impingement Reynolds number is represented by *Rej*, the cross flow Reynolds number is *Rec,* and the Nusselt number is defined as *Nu*.

The diameter of impingement hole rows is 1mm, the dimensionless hole space is 2～6, the dimensionless impingement distance is 0.5～4, the Reynolds number of jet flow is 5000～65000, and the cross flow Reynolds number is 0～5000.

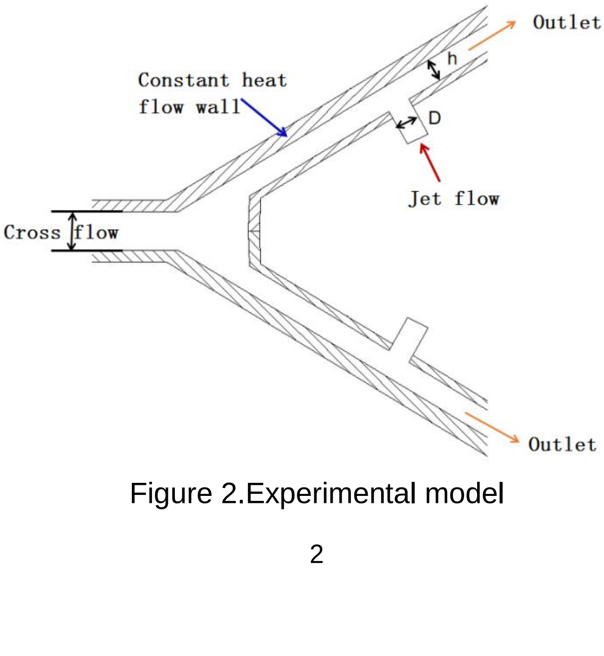


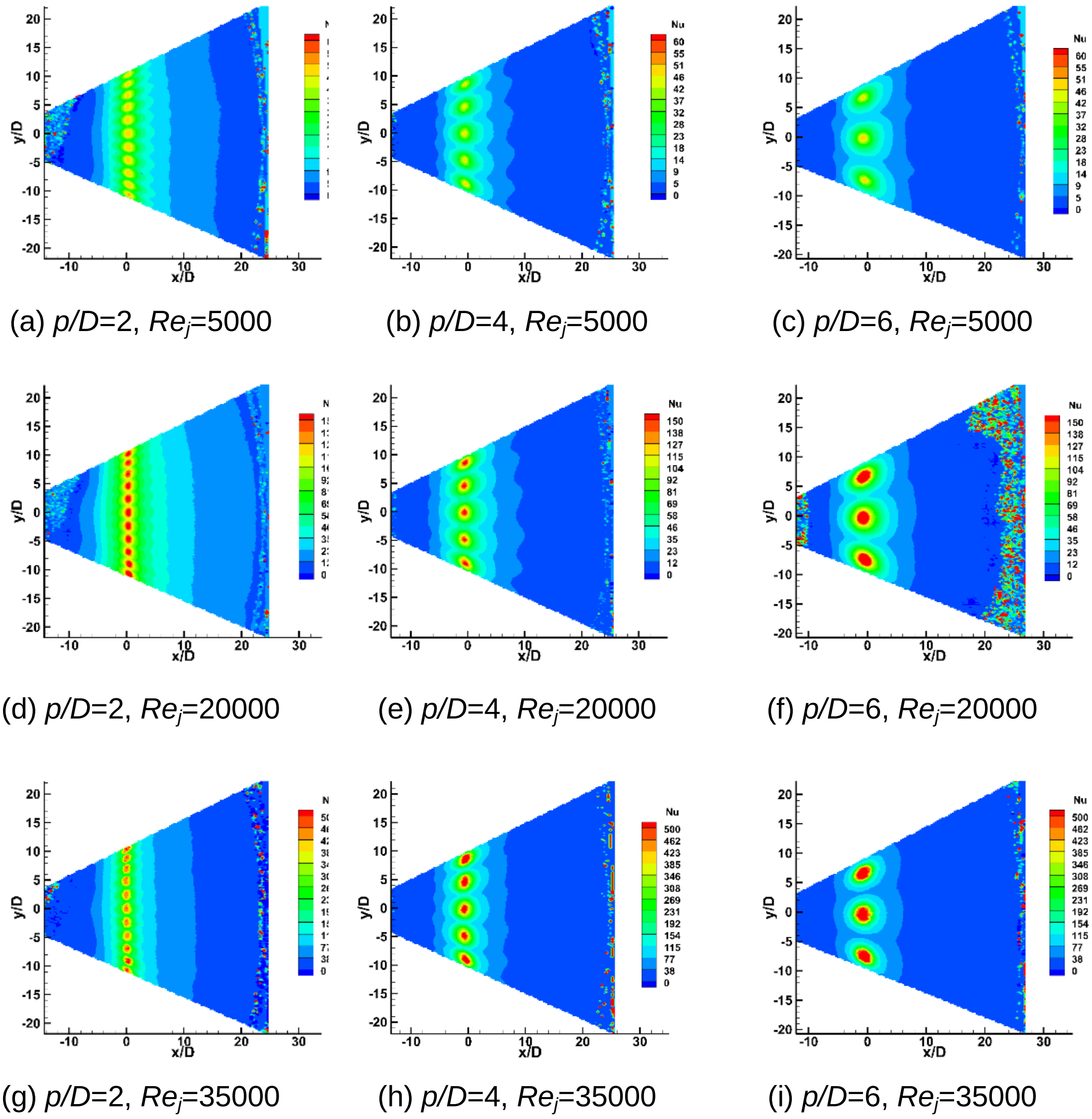
Figure 2.Experimental model

3. Experimental results & Discussion

3.1 Effects of hole space on impingement heat transfer characteristics

Figure 3 shows the distribution of Nusselt number with different hole space. It can be clearly seen from the figure that the Nusselt number in the stagnation point area is high and gradually decreases along the flow direction downstream of the stagnation point. This is because the boundary layer gradually develops and thickens from the stagnation point to the downstream, so the heat exchange gradually weakens along with the flow direction.

Secondly, comparing the Nusselt number distribution at different hole space, it can be found that the heat transfer in the stagnation area does not change significantly with the increase of hole space, while the low heat transfer area between adjacent holes is more obvious with the change of impingement hole space. This is because the influence between jet holes decreases gradually with the increase of hole space, and the low-speed area between jet holes increases with the increase of space. The distribution law of Nusselt number on the impact side wall is basically consistent with that of the impact plate, but due to the influence of the shape of the target surface, the distribution of Nusselt number on the impact side wall is fan-shaped rather than normal circular.



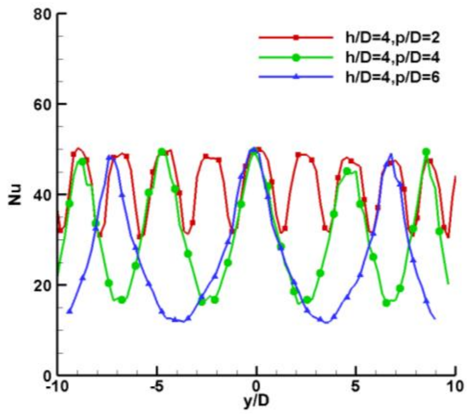
(a) *p/D*=2, Re_j=5000 (b) *p/D*=4, Re_j=5000 (c) *p/D*=6, Re_j=5000

(d) *p/D*=2, Re_j=20000 (e) *p/D*=4, Re_j=20000 (f) *p/D*=6, Re_j=20000

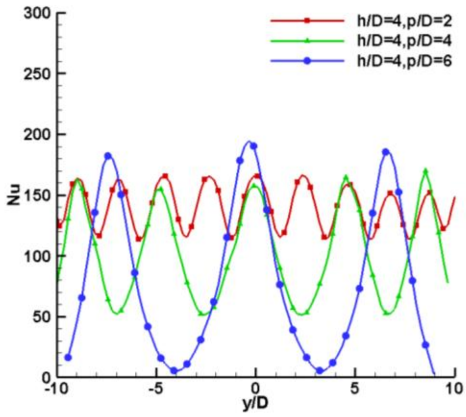
(g) *p/D*=2, Re_j=35000 (h) *p/D*=4, Re_j=35000 (i) *p/D*=6, Re_j=35000

Figure 3. The distribution of Nusselt number with different hole space

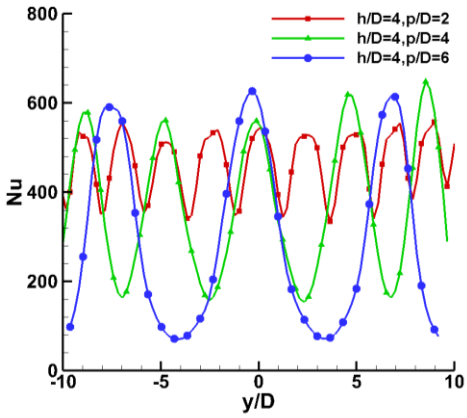
Figure 4 shows the distribution of Nusselt number under different hole space. It can be more clearly seen from the figure that the spacing of impact holes has no obvious effect on the heat transfer at the impact stagnation point. It has a very significant impact on the area between adjacent impact holes. With the increase of impact hole spacing, the heat transfer in this area decreases significantly and the Nusselt number decreases significantly.



（a）Re_j=5000



（b）Re_j=20000

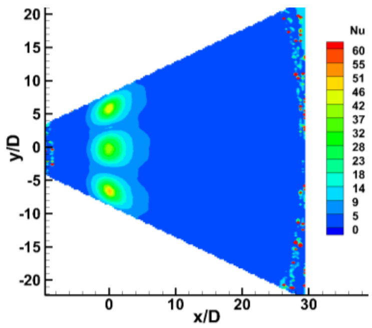


(c) Re_j=35000

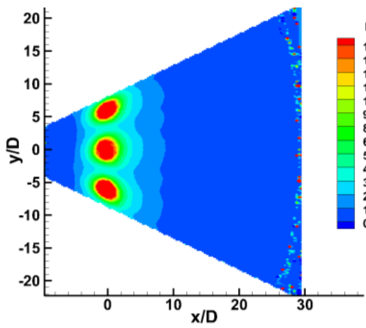
Figure 4. The curves of Nusselt number with different hole space

3.2 Effects of jet Reynolds number on heat transfer characteristics

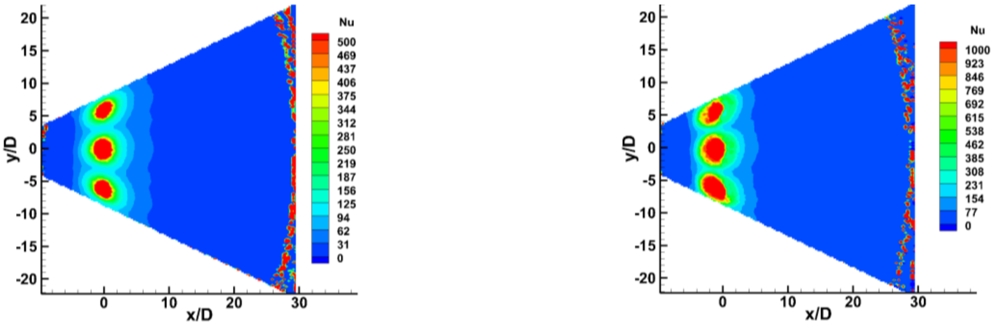
Figure 5 shows the distribution of Nusselt number under different Reynolds numbers without cross flow when the impingement distance is 2 and the hole space is 6. Firstly, it can be seen from the figure that with the increase of Reynolds number, the Nusselt number and heat transfer in the whole region increase significantly. This is because with the increase of Reynolds number, the velocity of jet impinging near the target surface increases obviously, the disturbance increases, and the heat transfer increases accordingly.



(a) Re_j=5000



(b) Re_j=20000



(c) Re_j=35000 (d) Re_j=50000

Figure 5. The distribution of Nusselt number under different Reynolds numbers

Figure 6 shows the distribution of Nusselt number along the flow direction when the impingement distance is 2 and the impingement hole space is 6. It can be seen more clearly from the figure that with the increase of Reynolds number, the Nusselt number in the whole region increases significantly, and the heat transfer increases significantly.

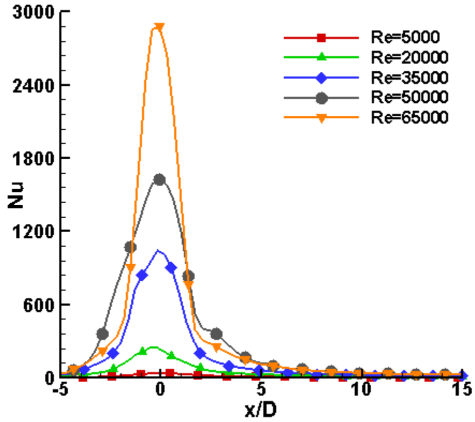
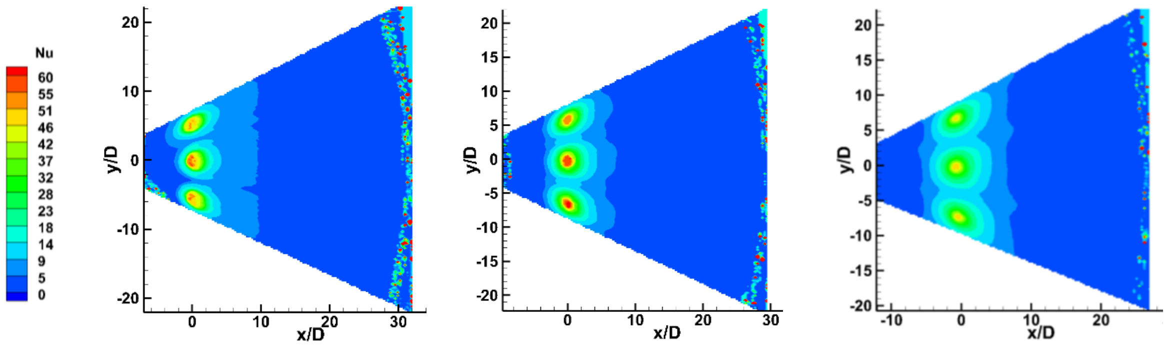


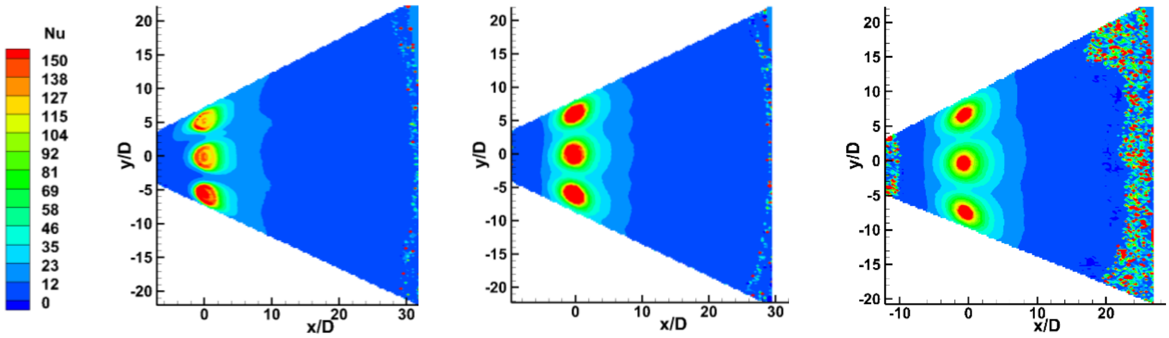
Figure 6. The distribution of Nusselt number along the flow direction with different jet Reynolds number

3.3 Effects of impingement distance on heat transfer characteristics

Figure 7 shows the distribution of the impingement distance on Nusselt number under the same impingement Reynolds number with the impingement hole spacing of 6. Firstly, it can be seen from the figure that with the increase of impingement distance, the Nusselt number in the stagnation point area first increases and then decreases. Secondly, when the impact distance is 0.5, the second peak of Nusselt number can be observed obviously. At the same time, when the impingement distance is 0.5, the heat transfer distribution in the impact area is closer to the sector, which is more vulnerable to the impact target surface.



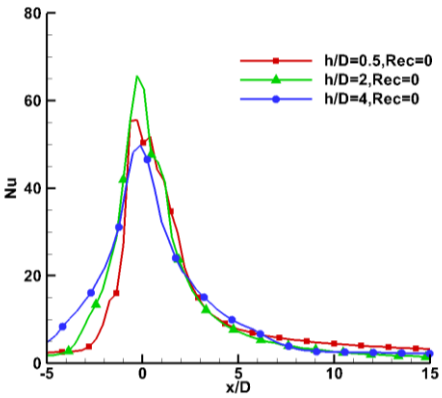
(a) h/D=0.5, Re_j=5000 (b) h/D=2, Re_j=5000 (c) h/D=4, Re_j=5000



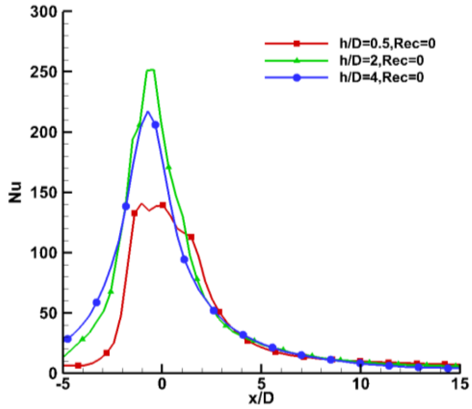
(d) *h/D*=0.5 Re_j=20000 (e) *h/D*=2, Re_j=20000 (f) *h/D*=4, Re_j=20000

Figure 7. The distribution of the impingement distance on Nusselt number

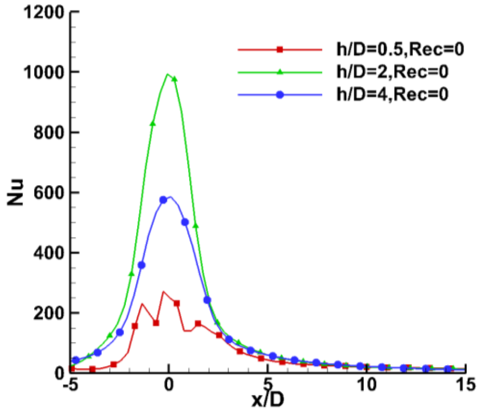
Figure 8 shows the Nusselt number distribution curve of impingement center along the flow direction under different jet Reynolds numbers. Firstly, it can be seen from the figure that the Nusselt number in the stagnation point area first increases and then decreases with the increase of impingement distance. Secondly, when the impact distance is 0.5, there is a double peak phenomenon in the stagnation point area, which is similar to that at the stagnation point of the leading edge.



（a）Re_j=5000,Re_c=0



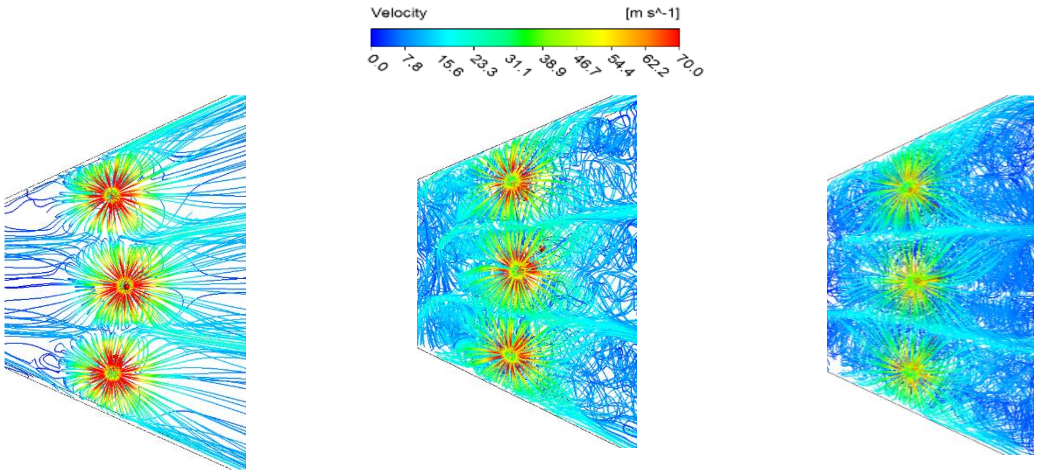
（b）Re_j=20000,Re_c=0



(a) Re_j=35000,Re_c=0

Figure 8. The Nusselt number distribution curve under different jet Reynolds numbers

In order to study the mechanism of impingement distance and cross-flow influence on heat transfer, the flow field of different distance was analyzed when the impingement hole space was 6 and the Reynolds number is 35000. Figure 9 shows the flow field distribution observed on the target surface under different working conditions. It can be found by comparing the distribution of different impingement distance. When the dimensionless impingement distance increases from 0.5 to 2,the disturbance of the flow near the stagnation point is enhanced. When the dimensionless impingement distance increases from 2 to 4,the heat transfer enhancement caused by the flow disturbance is not enough to compensate for the weakening effect of the velocity reduction on the heat transfer.

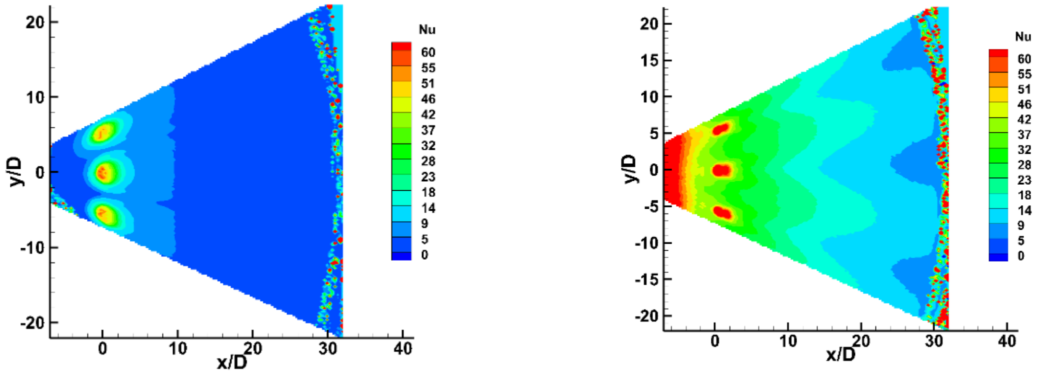


（a）h/D=0.5,Re_c=0 （b）h/D=2,Re_c=0 （c）h/D=4,Re_c=0

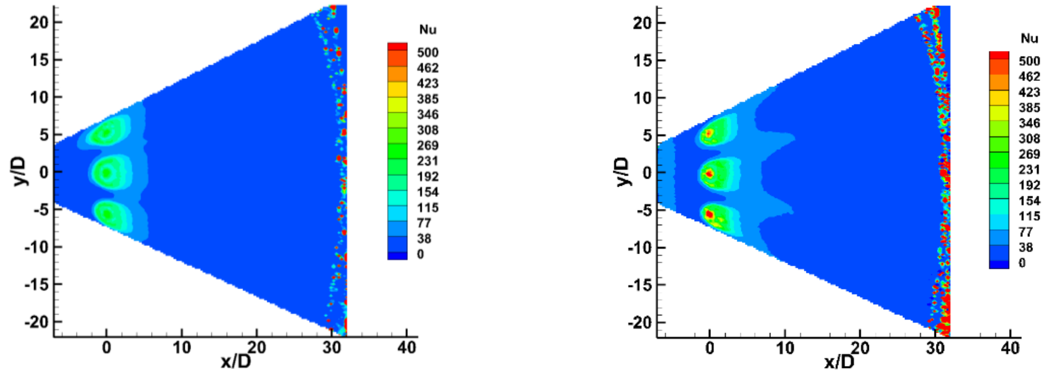
Figure 9. The flow field distribution under different working conditions

3.4 Effects of cross flow on heat transfer characteristics

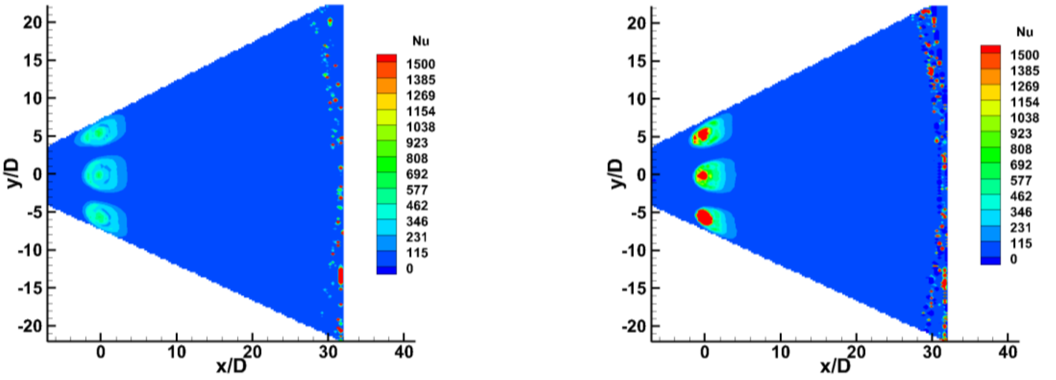
Figure 10 shows the Nusselt number of curved surface channel with cross flow. It can be found that the Nusselt number in the stagnation point region increases significantly after the addition of cross-flow. This is because after the cross flow is added, under the influence of the vortex structure behind the impact hole, more air flow enters the inter hole area, which enhances the heat transfer in the inter hole area.



(a) Re_j=5000,Re_c=0 (b) Re_j=5000,Re_c=5000



(e) Re_j=35000,Re_c=0 (f) Re_j=35000,Re_c=5000



(i) Re_j=65000,Re_c=0 (j) Re_j=65000,Re_c=5000

Figure 10. The Nusselt number of curved surface channel with cross flow

Figure 11 shows the Nusselt number ratio distribution curves of cone surface in the flow direction with and without cross flow. When at a small Reynolds number, the Nusselt number of the downstream area increases obviously. However, when the Reynolds number is larger, the Nusselt number downstream of the impingement area has no obvious increase. This is because this region is dominated by convective heat transfer. When the jet Reynolds number is larger, the cross flow does not obviously improve the downstream velocity, so the heat transfer enhancement effect is not obvious. In contrast, the addition of cross flow at a small Reynolds number makes the downstream velocity increase obviously, so the heat transfer increases.

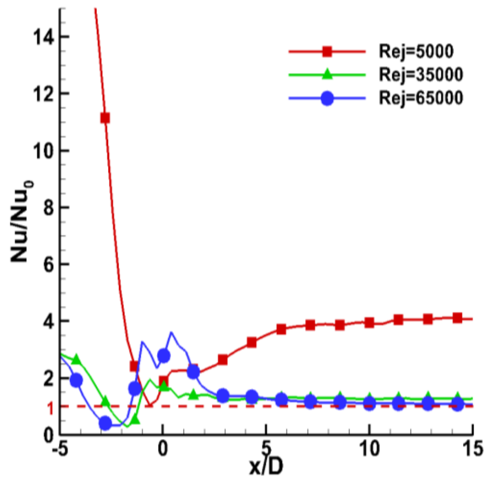
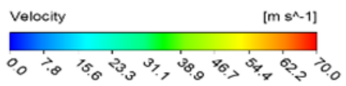
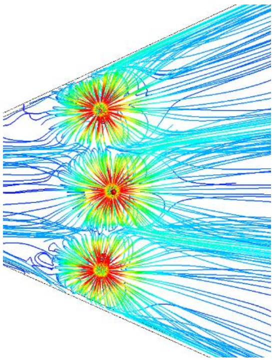


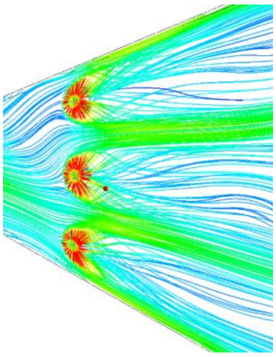
Figure11. The Nusselt number ratio curves with and without cross flow

In order to reveal the heat transfer mechanism, figure 12 shows the velocity contour distribution of the target surface with and without cross flow. It can be found that when the cross flow is added, due to the influence of the reverse vortex, more air flow enters the inter hole area, which significantly enhances the heat transfer. The addition of cross flow reduces the velocity in areas upstream of the impingement stagnation point, which makes the heat transfer in this area weakened.





(a) h/D=0.5,Re_c=0



(b) h/D=0.5,Re_c=5000

Figure 12. The velocity contour distribution of the target surface with and without cross flow

4. Conclusions

In this study, the jet impingement heat transfer characteristics of aero-engine inlet cone with cross flow were investigated by experiments. The following conclusions can be obtained.

1、With the increase of the space between the impact holes, the Nusselt number in the area between the impact holes decreases obviously, which leads to the decrease of the average Nusselt number in the impact area.

2、The jet impingement Reynolds number is the main factor affecting the side wall impingement heat transfer. With the increasing of Reynolds number, the velocity of impinging jet and turbulent kinetic energy increase, which significantly enhances the heat transfer.

3、The impingement distance is the main factor affecting heat transfer. With the increase of impact distance, the local Nusselt number first increases and then decreases. When the impingement distance is small, the cross flow can enhance the heat transfer in the impact stagnation zone. When under the larger impact distance, the cross flow weakens the heat transfer in the stagnation zone.

5. Contact Author Email Address

Xinwei Jiang: 690509242@qq.com

6. Copyright Statement

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