Heat transfer enhancement mechanism of jet impingement on aeroengine curved surface using large eddy simulation

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Abstract. Jet impingement is widely used in anti-icing and de-icing of aeroengines. To improve the efficiency of anti-icing and de-icing, heat transfer in jet impingement flow should be further enhanced. By using large eddy simulation (LES) method, jet impingement flow was analysed in time-domain and spatial-domain. It was revealed that the jet flow has quasi-periodic characteristics in time, and heat transfer is dominated by vortex structure. In addition, the impinged surface curvature has a certain influence on the spatial distribution of Nusselt number. Better heat transfer effect can be achieved by inducing more vortices and applying proper surface curvature.

1. Introduction

Due to its high efficiency in heat and mass transfer, jet impingement is widely used in industry, including turbine blade cooling, anti-icing of aircraft wings, anti-icing of aero-engine air inlet, and cooling of electronic components. The secondary air system of an aeroengine plays the role of cooling, sealing and anti-icing, which needs to bleed air from certain stages of the compressor. The compressor consumes the work produced by the gas in turbine, which should have been used to compress the air. The primary purpose of high-pressure air in compressor is to generate thrust. Therefore, the more compressed air is required for the second air system, the less compressed air will be used for thrusting the aircraft. As a result, the efficiency of the engine will decrease. Above all, it is of vital importance to improve the heat transfer efficiency of jet impingement, and further reduce the air mass flux of secondary air system. To achieve this goal, many researchers have done a lot of research on this, including both simulation and experiment.

Many experimental studies on the influence of various geometric factors and aerodynamic parameters on jet impingement have been carried out. Lee et al. [1] studied how curvature of impinged surface and jet Reynolds numbers(Re) influence the heat transfer of fully developed jet impingement and drew a conclusion that the Nusselt number(Nu) increased with the increase of surface curvature. The authors thought that the larger curvature lead to a thinner boundary layer and they pointed that the second maximum of local Nu number was caused by the transition of boundary layer. Cornaro et al. [2] studied the flow structure of circular jet impingement on plate surface, concave surface and convex surface with visualization method, and clearly captured the vortex structure and the interaction between vortices and impinged surfaces in the process of jet development. It is found that the
influence of curvature on the structure of the flow field becomes uncertain when the non-dimensional jet-surface spacing $H/d$=4, because the radial vibration is strong at this condition. It's also not clear when $H/d$=1, because the axial vibration is too strong. Katti et al. [3] compared the effects of jet-jet spacing, jet-surface spacing and surface curvature on the static pressure distribution of the impinged surfaces. The experimental facility of Fenot et al. [4] was an array of jets impinging on concave surface, and they focused on the analysis of the variation of Nu with jet temperature and surface curvature, but did not explain the reason for the formation of this distribution. Zhou Ying et al. [5] analyzed the influence of geometric factors and Reynolds number on the heat transfer characteristics, and drove the conclusion similar to that of Lee et al. [1]. Patil and Vedula [6] also investigated the heat transfer of jet arrays impinging on concave surfaces. The influence of jet tube length, jet-surface spacing and jet Reynolds number was studied and a evaluation standard for jet impingement was proposed. Hadipour [7] used Reynolds Averaged Navier Stokes (RANS) simulation and experiment to study the heat transfer characteristics of jet impingement with little jet-surface spacing, proving that SST model can predict the heat transfer accurately.

Numerical simulation of jet impingement is also a hot topic because of its low cost. Taghinia [8] compared the numerical prediction results of heat transfer of jet impingement on curved surface with the experimental results from literature, including one RANS turbulence model and two LES turbulence models. The prediction results of LES model were more consistent with the experimental results. Zuckerman and Lior [9] summarized many standard and improved turbulence models and evaluated their ability to predict the flow field of jet impingement. He and Liu [10] simulated the flow structure and heat transfer characteristics of circular nozzle jet and lobe jet by LES, and believed that the reason of the second maximum value of local Nu was the generation of secondary vortex. Dairay et al. [11] conducted direct numerical simulation (DNS) of jet impingement under the condition of full turbulence for the first time. The relationship between the second peak of the mean Nu in the radial distribution and the vortex structure is studied. Especially, to understand the increase of average heat transfer within the range of $1.5 \leq r/D \leq 2$, the unsteady characteristics of the flow were analyzed by using the DNS results. Rohlfis et al. [12] studied the Nu distribution when the circular jet impinged on the plate under the condition of low jet Reynolds number (Re= 392,1177 and 1804) and analyzed the reason for the first and second peak of Nu. The influence of jet velocity distribution on flow and heat transfer is analyzed using the flow field parameters such as velocity and pressure.

It can be seen that most of the research focuses on the influence of geometric factors and aerodynamic parameters on the heat transfer distribution, such as the shape of jet, the spacing between jets and impinged surface, jet Reynolds number and curvature of the surface, etc. In addition, many empirical formulas describing Nu distribution were summarized in these research work, with limited accuracy. As for the local heat transfer mechanism of jet impingement, various researchers held different opinions. Primary vortex, secondary vortex, local acceleration and transition of the boundary layer have been mentioned. This paper will analyze the fundamental factors that affect heat transfer behavior.

2. Computational tools and models

2.1. Computational tools

RANS method uses isotropic turbulence model, which is efficient to calculate but has limited accuracy. DNS resolves the N-S equation directly and it can get the flow characteristics of all scales as if the mesh is fine enough, but it is time-consuming when the grid resolution is extremely high. LES is able to capture the flow characteristics larger than the filter size, while the characteristics less than this size are modeled by the sub-grid stress (SGS) model, which guarantees the accuracy and efficiency of the calculation simultaneously.

The calculation tool used in this paper is Ansys Fluent, and dynamic Smagorinsky model is selected as the SGS model. Dynamic model can determine the model coefficients based on the
dynamic calculation process. Compared with Smagorinsky model, the numerical dissipation of the dynamic Smagorinsky model is smaller.

2.2. Geometric model and mesh

The object studied in this calculation is a circular jet impinging on a concave surface (Figure 1), of which the jet diameter $d$ is 2mm and the jet tube length is 2 mm. The non-dimensional jet-surface spacing $H/d = 4$, where $H$ is distance between jet outlet and the stagnation point. The curvature $Cr$ of impinged surface is 0.05, 0.1 and 0.125 respectively, where $Cr = d/D$ and $D$ is diameter of the impinged surface. The inlet velocity is constant and the jet Re is 10000, ignoring the compressibility of air. The impinged surface is cooled, with a heat flux $q = -2000$ W/m². Hot air is jet from the tube with a temperature of 400K. Nu number is adopted to represent the heat transfer effect, where Nu is defined as

$$Nu = \frac{hd}{\lambda} \quad (1)$$

Where $\lambda$ is conductivity of air and $h$ is convection heat transfer coefficient. $h$ is derived from

$$h = \frac{q}{T_w - T_{jet}} \quad (2)$$

![Figure 1. Geometry and mesh of the jet impinging on a concave surface (Cr = 0.1).](image_url)

| Table 1. Parameter settings of case1-3. |
|-----------------------------------------|
| Case | Curvature | H/d | Grids Number |
|------|-----------|-----|--------------|
| Case1 | 0.05      | 4   | 6,350,000    |
| Case2 | 0.1       | 4   | 5,977,000    |
| Case3 | 0.125     | 4   | 7,175,000    |

LES simulation shows great sensitivity to grid scale. The mesh scale used in this study is the same as a previous calculation of a jet impingement on a plate surface done by the authors. Three sets of grids number were compared in a case of $H/d = 1$, of which the geometry and average Nusselt number are shown in Figure 2 and Figure 3 respectively. It can be seen that when 1612800 grids were used, the results were similar to that of 2668800 grids but obviously different from that of 522000 grids. The results reveal a fact that grids scale in the second mesh is fine enough to calculate the heat transfer. To capture the flow details as much as possible, the refined mesh, with grid scale the same as the third mesh in the flat case, was used to simulate curved surface jet impingement. The finial grids numbers are 6350000, 5977000 and 7175000 respectively for case1-3.
In addition, LES has strict requirement for the grids number in boundary layer and $y^+$ is recommended to be less than 0.5. Figure 4 (a)-(c) show the $y^+$ value of case1-3. The thickness of the first grid layer in direction normal to surface is $1e^{-6}$m. It can be seen from Figure 4 that $y^+$ on most area of the impinged wall is less than 0.5 and satisfy the requirement of LES.

Comparison between results of this LES method and experimental results [1, 6, 13] from other researchers is shown in Figure 5 and Figure 6. Both in the case of plate impingement (Figure 5) and curved surface impingement (Figure 6), non-dimensional jet-surface spacing $H/d=4$ and jet Reynolds number is 10000. It can be seen that Nu in the zone of $s/d \leq 4$ is close to the experimental data in both cases, which illustrates that the LES method is accurate in simulating the flow and heat transfer.
3. Results and discussion

3.1. Quasi-periodic characteristics of the jet impingement flow field

Vortex is formed at the exit of the jet, with an unclosed ring structure, and moves downward with the fluid, as showed in Figure 7 (a)-(e). The vortex has enough space after formation, so it grows in the downward movement. When approaching to the impinged surface, it shrinks due to limited space and grows again after contact with the surface.

Figure 7. Vortices position and shape at different instant, with time step $\Delta T = 5e^{-6}$ between each map.
The generation of vortices is influenced by the former vortex. Only after the former one moves away can there be enough space to form a new vortex ring. This process is demonstrated by vortex position at different time in ZOY plane (Figure 8(a)), as shown in figure 7. The arrow points at the same vortex at different instant, showing its position and shape. The way how the vortices are generated and developed determines how the impingement heat transfer changes with time. This will be analysed in section 3.2.

![Diagram of vortices and local Nu](image)

**Figure 8.** Position of (a) YOZ plane and (b) the ring selected to obtain the local Nu.

Because generation and impingement of vortices are intermittent, the whole flow field presents quasi-periodic characteristics. In this example, the jet velocity is 130.95 m/s, and the mean time between two maximal local Nu is about 2.8e-5s, with the Nu-time relationship shown in Figure 9. The local Nu showed in Figure 9 is a local average in a ring area of $1d \leq r \leq 1.1d$, which is highlighted in Figure 8 (b). Similar area-averaged local Nu fluctuation with time is adopted in case 1 and case 2. Although the time span between two maximum or minimum of local Nu changes slightly, the phenomenon is obvious that a sequence of vortices impinging on the curved surface leads to a regular fluctuation of local Nu. When the curvature is changed, the frequency is somewhat different from case 1 because of the different flow space.

![Graph of Local Nu](image)

**Figure 9.** Local nu of the monitored position on the curved surface. (Cr=0.05).

3.2. Analysis of local enhancement of heat transfer.

Since the variation of Nu along the wall surface is similar under different curvature, only one curvature $Cr = 0.05$ is analysed here. The Nu contour map is compared with the velocity, pressure, vorticity and streamline near the wall at the same moment. Instead of comparing Nu data on a line(X=0) with flow features of YOZ plane, full-field analysis is chosen because the 2D data cannot reflect 3D features of flow field and heat transfer. Lattices are pictured to recognize the position clearly.
Figure 10. Nu distribution on the impinged surface.

It can be seen from Figure 10 that the position of high Nu presents a ring distribution, and the pressure also presents a ring distribution, as shown in Figure 11. The ring of low pressure is consistent with the ring of second maximum Nu. Normally, low-pressure corresponds to the vortex structure, and as can be seen from Figure 10, Nu at the corresponding position drops sharply after the pressure ring is broken, which shows that the high Nu and low pressure (or vortices) are closely related. However, although no particularly low pressure exist on the wall of the stagnation zone, Nu still has a peak zone with ring shape.

Figure 11. Pressure distribution on the impinged surface.

Figure 12. Vertical view of vortex structures.

Figure 13. Velocity iso-surface of impinged surface, \( V = 105 \text{m/s} \).

There are two whole vortex ring structures in Figure 11, and the outer vortices are broken. The two whole vortex rings are in line with the high Nu number rings in figure 9. The above analysis shows that the local enhancement of the surface heat transfer is caused by the impingement of the vortex structure. However, the mechanism of how vortex structure reinforces the heat transfer needs to be analysed further.

By comparing the distribution of Nu, vortex structure, pressure and velocity (figure 12) on the surface, it can be found that the positions of low pressure, high speed and vortex structure are corresponding. Corresponding physical truth on the surface is that the flow slows in the stagnation zone and the pressure increases rapidly. However, vortices formed outside the jet hit to the wall, leading to the local low pressure ring outside the high pressure zone. The pressure difference drives the fluid to accelerate, resulting in the high Nu. From the location of the streamline and the Q contour, it also can be seen that the surrounding air is absorbed into the jet body under the effect of viscosity and velocity gradient. The vortex shrinks due to the high pressure in the stagnation zone and rapidly outside the high-pressure zone. When the vortex ring expands to a certain extent, the speed decreases...
because of continuity, so the vortex ring breaks down. This vortex distribution near the surface leads to the change of speed and flow direction, and finally determines the heat flux or temperature of the wall.

Figure 14. Nu number comparing with the streamline on (a)ZOY plane and (b)ZOX plane.

ZOY plane and ZOX plane are extracted to analyse the relationship between the heat transfer of the wall and flow details near the wall, as shown in Figure 14. It can be found that the location of maximum Nu is slightly outer than position of the vortex ring, instead of on centre the vortex. Figure 15 presents the comparison of velocity on ZOY plane and Nu distribution on line of X=0, which also indicates that the position of maximum Nu is not completely the same as the position of maximum velocity, but vicinity of the position of maximum velocity. It is interesting that maximum Nu is related to the positive and negative switching of velocity in Z direction (Figure 15). The local maximum of Nu always appears in the position where velocity of Z direction changes from negative to positive, so heat transfer is supposed to be related to the direction of the velocity near the wall.

Figure 15. Compare of Nu, magnitude of velocity and velocity in z direction.
The streamlines in Figure 16 can clearly show the direction of flow on the ZOY plane. The flow direction near the surface is affected by the impingement of the vortices on the surface. As mentioned earlier, vortices hit on the surface with a certain frequency, so at the same moment there are vortices in some positions, while other positions are between two vortices. Before passes positions with vortices, the fluid is carried into the bottom of the vortex and after this position, fluid is carried away from the surface. When flow into the surface, fluid velocity in Z direction is negative, much hot air is carried into the boundary layer so the heat transfer is enhanced. On the contrary, when velocity in Z direction is positive, the hot air is carried far from the surface, so the heat transfer is weakened.

3.3. Time statistical Nu distribution.

More attention is payed to the statistical heat transfer effect during a certain time period in engineering applications, so the statistical Nu in a time length of 100 times of the period, \( \overline{Nu} \), is selected to represent the average heat transfer effect. The distribution of \( \overline{Nu} \) is showed in Figure 17.

From Figure 17, it can be seen that the distribution of \( \overline{Nu} \) in s direction, with the curvatures of impinged surface are 0.05, 0.1 and 0.125 respectively. The \( \overline{Nu} \) of the case \( Cr = 0.05 \) is similar to that of \( Cr = 0.125 \), but the \( \overline{Nu} \) of \( Cr = 0.1 \) is a little smaller. Similar \( \overline{Nu} \) distribution patterns are presented along X direction, and the \( \overline{Nu} \) of \( Cr = 0.05 \) is almost the same as that of \( Cr = 0.125 \) in the stagnation zone and zone of \( x/d > 3 \).

The simulation result of case2 is different from that of the other two. First \( \overline{Nu} \) of \( Cr = 0.1 \) has no obvious symmetry, and if only a few cycles are taken into account, the \( \overline{Nu} \) distribution is very uncertain, and only the average of a long period of time can show a symmetric distribution. The reason for this phenomenon is that the jet flow of case2 has a strong radial instability, resulting that the stagnation point is not at the geometric stagnation point exactly. This was also measured by Cornaro et al [2] and only occurred when jet-surface spacing \( H/d = 4 \). Second, the \( \overline{Nu} \) is smaller than that of the other cases. This phenomenon reflects that heat transfer of non-vertical jet impingement is weaker than that
of the vertical jet impingement. As a result, when designing a jet impingement structure, this kind of conditions that will result in unsteady oscillation should be avoided. The statistical averaged Nu has a maximum, and then decreases monotonically. The location of this maximum \((r/d)_{\text{max}}\) is between \(r/d=0.5\) and \(r/d=1\). In the zone of \(r < (r/d)_{\text{max}}\), \(\overline{Nu}\) is relatively large while in the zone of \(r > (r/d)_{\text{max}}\), \(\overline{Nu}\) decreases rapidly and keeps constant in \(r/d > 4\). The influence of curvature on the calculated model is whether the structure can form a stable jet impingement. When \(Cr = 0.05\), \(0.125\), the flow field is stable, and the distribution of \(\overline{Nu}\) is similar. However, when \(Cr = 0.1\), radial instability increases. The statistical average result is no longer similar to the instantaneous result and the peak and symmetry become uncertain.

4. Conclusion
In this study, jet impingement is analysed from spatial and temporal perspectives. Main conclusions are listed below:

(1) Due to the formation, shrinking, growing and rupture of vortex rings, distribution of Nu on curved surface is quasi-periodic.

(2) There are peak values of instantaneous Nu on the impinged surface and the largest Nu locates at the outside of the stagnation zone. Heat transfer is dominated by the vortex structure.

(3) There is one peak value of statistical averaged \(\overline{Nu}\) and it is influenced by curvature of the impinged surface.

The above conclusions can provide basis for the anti-ice structure design, such as adding rough structure on the surface to change interaction between surface and vortices and changing the curvature of the icing surface without affecting the aerodynamic performance.

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