A NEAR-FIELD INVESTIGATION INTO THE EFFECTS OF GEOGRAPHY AND COMPOUND ANGLE ON THE FLOWFIELD OF A ROW OF FILM COOLING HOLES

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ABSTRACT
The goal of this study was to determine the effects that hole geometry and compound angle have on the near-field downstream from a row of jets injected into a crossflow. Velocity and vorticity fields are presented in cross-sectional planes oriented perpendicular to the mainstream flow. Instantaneous field measurements were obtained using particle image velocimetry (PIV). Data were recorded at locations of 0, 1, 2, and 3.5 hole diameters downstream of injection for three different hole geometries inclined at 35° to the mainstream flow. These geometries consisted of a cylindrical hole, a 12° laterally-diffused hole, and a 15° forward-expanded hole with compound angles of 0°, 45°, 60°, and 90°. Data are presented for a blowing ratio of 1.25 and density ratio of 1. The influences on jet penetration, coverage width, flow structure elevation, and flow structure separation for each configuration are discussed. Vorticity is presented in terms of field distribution and peak magnitudes. These studies show the degradation of the counter-rotating vortex pair into a singular, recirculating structure as the compound angle increases. Peak levels of vorticity are not encountered until between one and two diameters downstream of injection.

BACKGROUND
Jets in crossflow are a common occurrence in many engineering systems. One of the most common applications of these jets is in the gas turbine industry, used to provide film cooling for the surfaces of the turbine blades higher for greater operating efficiency. This study focuses on the flow characteristics in the near-field of film cooling holes and the effects of the hole geometry and compound angle on improving the flow for film cooling. It is desired to minimize mixing of the jet with the crossflow to maximize film cooling effectiveness. Mixing may be enhanced due to a result of strong secondary flows and turbulence. This study presents detailed information concerning the lateral flow characteristics just downstream of a jet film hole as affected by hole geometry and compound angle (angle of jet injection relative to the main crossflow orientation).

A primary concern is the strong secondary vortex flow structure that is generated in the film hole and how this propagates downstream as it mixes with the crossflow. These vortices can reduce the film cooling effectiveness by creating aerodynamic lift within the coolant jet, thus removing the coolant from the downstream surface. These vortices, due to their rotational direction, can cause the high temperature free stream fluid to flow under the coolant jet, which also exposes the turbine blade to the higher temperature combustion gases. By modifying the film hole geometry, it is possible to alter the effect of these flow structures.

There have been numerous studies investigating the downstream flowfield present for jets injected normally into a crossflow. Ajersch, et. al. (1995), found a counter-rotating vortex pair for blowing ratios of 1.5 and 1.0 but were not as distinct for a blowing ratio of 0.5, in which case the jet was too weak to penetrate the turbulent boundary layer formed upstream of injection. Andreopoulos and Rodi (1984) found that in the wake region, of circular hole injection normal to the crossflow, a velocity deficit and small gradients of...
streamwise velocity develop with a size that increases with blowing ratio. The low pressure in the wake region induces lateral inward motion and a downwash of the bent-over jet. Other studies of jet injection normal to a crossflow include Crabb, et. al. (1981), and Fric and Roshko (1994).

Flow characteristics of inclined jet injection have been studied by Adler and Baron (1979) computationally, with injection angles from 20° to 90°. Bergeles, et. al. (1977) injecting at 30° to the mainstream noted recirculation for a range of blowing ratios. Gogineni, et. al. (1996) used PIV to investigate the near field of holes injected at 35° to the mainstream, utilizing periodically forced cooling to simulate a vane wake on the rotor of a turbine. They found that increased levels of turbulence and periodically forced flow augment the spreading of the jet. Leylek and Zerkle (1994) show that the vortex structure in the hole is caused by the large turning angle of the flow from the plenum into the jet. Pietrzyk, et. al. (1989) presented velocity contours for round holes injected at 35° to the mainstream. As the counter-rotating vortices are convected downstream, they entrain surrounding fluid and grow in size. For lower velocity ratios the vortices do not extend to the symmetry line between adjacent jets. For the highest velocity ratio, however, the vortices cause significant downward flow towards the wall at this symmetry line at a downstream distance greater than 5 hole diameters. Other studies include Lee, et. al. (1994), and Rydholm (1996) for various momentum and density ratios.

A number of studies have addressed the issues concerning non-circular jet holes. Findlay, et. al. (1996) studied inclined square holes. At a velocity ratio of 0.5, the vortex pair did not develop by 8 diameters downstream of injection. The injected jet did not penetrate beyond the turbulent boundary layer generated upstream of the hole. Hyams and Leylek (1997) computationally showed the resultant velocity fields from five inclined hole geometries. Thole, et. al. (1996) and Wittig, et al. (1996) presented studies which incorporated various shaping of film cooling holes. These studies show that the jet penetration into the freestream, the velocity gradients at the hole exit, and turbulence generation downstream of the hole can be significantly reduced by hole shaping. Also, forward-laterally expanded holes allow ingestion of mainstream fluid into the windward side of the cooling hole, thus reducing the performance of the film cooling jet.

Brittingham and Leylek (1997) computationally investigated the effects of compound angle on the downstream flowfield for three different hole geometries. Velocity contours show the collapse of the vortex pair to a singular vortex as the compound angle increases. Investigation into the flow within the film hole itself showed a separation region for the forward diffused case that was not present for the laterally diffused case.

In an attempt to better understand flow geometry effects on film cooling the present study investigates the flowfield downstream of three distinct hole geometries: a cylindrical hole, a 12° laterally diffused hole, and a 15° forward diffused hole with compound angles of 0°, 45°, 60°, and 90°. Experiments were performed using hot wire anemometry to characterize the upstream conditions of the mainflow and PIV to measure the lateral or secondary flow structures in the near region of the jet-crossflow interaction. The two dimensional velocity fields were used to calculate streamwise vorticity using a central difference scheme. PIV was applied to obtain full-field, instantaneous velocity measurements at particular planes of interest in the near field immediately downstream of the coolant injection holes. Data were obtained for the conditions given in Table 1.

EXPERIMENTAL FACILITIES

The experiments were conducted in an existing open-loop, suction-type wind tunnel with a 9:1 area reduction ratio. An interchangeable test section having a 0.6 m by 0.6 m cross section and length of 2.4 m was utilized for experimentation. The sides and top of the test section contain large plexiglas windows to allow optical access necessary for flow visualization. A foreign gas injection supply line is configured so that either carbon dioxide or air can be used as the jet gas. This is to allow for variation in the density ratio of jet to mainstream fluid. The jet supply gas passes through a shell-and tube heat exchanger in order to regulate the supply temperature. The flow rate is measured just upstream of the plenum. The jets are machined into a plate which forms the top wall of the plenum. This plate is interchangeable to allow different jet geometries to be inserted. The geometries of the three holes used in this study are shown in Figures 1.

TABLE 1: Experimental Conditions. Hole inclination angle is 35° for all cases.

<table>
<thead>
<tr>
<th>Hole Geometry</th>
<th>Blowing Ratio</th>
<th>Density Ratio</th>
<th>Compound Angles (°)</th>
<th>Streamwise Planes(y/D)</th>
<th>Transverse Planes (x/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td>1.25</td>
<td>1</td>
<td>0, 45, 60, 90</td>
<td>0</td>
<td>0, 1, 2, 3.5</td>
</tr>
<tr>
<td>Laterally Diffused</td>
<td>1.25</td>
<td>1</td>
<td>0, 60, 90</td>
<td>0</td>
<td>0, 1, 2, 3.5</td>
</tr>
<tr>
<td>Forward Diffused</td>
<td>1.25</td>
<td>1</td>
<td>90</td>
<td>N/A</td>
<td>0, 1, 2, 3.5</td>
</tr>
</tbody>
</table>
The test surface downstream of jet injection was fabricated from a 16 mm x 458 mm x 700 mm plexiglas plate painted flat black to minimize light reflection. The top and sides of the wind tunnel test section are clear plexiglas for optical access. A glass insert in the test allows optical access for the CCD camera used to observed transverse planes using a mirror approximately 320 mm downstream of the holes.

PIV data were collected in the streamwise direction and normal to the mainstream flow. A pulsed Nd:YAG laser was used to illuminate the flow field with separation times between pulses ranging between 10 µs to 70 µs with a pulse time of 6 nanoseconds. Separation times were chosen based on the estimated velocity component of the flow that was aligned with the laser sheet. The flow was seeded with particles injected with an ultrasonic nozzle delivering a suspension of methanol and 2 µm diameter titanium dioxide particles into the jet supply plenum. The seed mixture exited the plenum through the row of film holes. The double pulsed images were captured with a black and white CCD camera. The images were digitized and analyzed with commercially available software to determine the velocity and vorticity fields.

Boundary layer suction was used to obtain a uniform velocity profile at the leading edge of the test surface. The two-dimensionality of the flow field varied less than 5% across the test section at the leading edge of the test surface. The velocity profile at the center of the leading edge was uniform to within 1%. A 0.584 mm diameter trip wire, 14 mm downstream of the leading edge ensured a turbulent boundary layer at the jet exit. 83 mm (10D) upstream of injection and at the leading edge of the film holes the boundary layer thickness was 4.6 mm and 5.8 m, respectively and the velocity profile is well represented by a one-seventh power law. The freestream turbulence intensity was approximately 0.85%. For all transverse studies having a compound angle other than 0°, the flow is exiting the jet and flowing from left to right when viewing the experimental data. Data are presented looking in the upstream direction.

RESULTS

It is well documented that when jets are injected into a crossflow, a pair of counter-rotating vortices is formed. These vortices are evident immediately upon exiting the hole, at a location of x/D = 0, and can be seen in Figure 2a. At this location, the width and height of the jet measure 0.97D and 1.84D, respectively. The counter-rotating vortices are elevated 0.3D from the surface and are 0.86D apart at their centers. The vortices are centered about the tangent point of the hole, with offsets for the left and right vortices of -0.41D and 0.46D measured from a line extended in the streamwise direction passing through the point on the hole that is furthest downstream.

As shown in Figure 2b, two diameters downstream, the cross section of the injected jet indicates penetration of 1.23D into the mainstream with coverage of 1.84D of the test surface. Each of the two vortices has moved closer to the test surface. The center of each vortex is 0.46D from the surface. The cores of the structures are 0.82D apart, with jet offsets of 0.43D and 0.38D, respectively. The vortices at this location have enlarged and their magnitudes have diminished.

In comparison to the α = 0° case, Figure 2c shows the velocity vector plot for the α = 90° case, at x/D = 2. The jet penetration at this point is 1.47D into the mainstream flow. The vortex no longer has its distinctive, circular shape. It is centered with an offset of 0.62D and is elevated 0.62D.

The velocity distribution one diameter downstream of injection is shown in Figure 3a, for the laterally diffused hole geometry at α = 0°. The flow pattern indicates that the vortices lie closer to the test surface compared to the cylindrical case. The elevation of the two vortices at this location is 0.37D. The separation distance of the vortex centers is 1.33D, which are offset from the tangent point a distance of -0.83D and 0.50D. At this downstream location the jet has increased its penetration into the crossflow to 1.20D and has spread to cover 2.39D of the test surface.

By compounding the laterally diffused hole for α = 90°, at a downstream location of x/D = 1, shown in Figure 3b, the cross-section of the jet has a singular, circular shaped vortex. The one vortex center has moved further from the surface and is located at 0.87D, with an offset of -0.37D. The penetration has increased to 1.65D while the surface coverage has decreased to 1.74D. This shows less surface protection provided by the laterally diffused jet at this compound angle.

For the forward diffused hole at x/D = 1 and α = 90°, there is no distinct vortex present, (not shown) but rather there is an angular flow structure without complete circulation. This structure is centered -0.2D from the tangency line and elevated 0.58D. At approximately two thirds the distance between adjacent jets, a second angular flow structure in the flow field is observed, however little or no rotation is noted. The jet penetrates 1.39D into the crossflow at this point.

The width of the surface covered by the jets for the cylindrical and laterally diffused geometries is given as a function of x/D in Figure 4a. This width was determined by the presence of seed particle pairs observed in the PIV images at the surface (since all seed particles were injected into the jet and not the mainstream). The amount of the test surface covered by the laterally diffused hole is greater than that of the cylindrical hole for the entire region studied. It appears that the cylindrical hole maintains approximately the same amount of lateral coverage for the first 3.5 diameters downstream of injection, whereas the laterally diffused case exhibits a localized maximum at x/D = 1. Beyond this location, the jet coverage begins to decrease. This is most likely due to a more rapid decay in the vortices present in the flow fields. These vortices are positioned further apart and are weaker for the laterally diffused geometry, and thus tend to decay more rapidly than the cylindrical case. As these vortices weaken there is greater mixing with the mainstream.
fluid and thus, a decrease in the coverage area. However, the laterally diffused hole geometry still covers approximately 45% more area than the cylindrical hole at 3.5D downstream.

The separation distance between the centers of the flow structures is also greater for the laterally diffused hole than it is for the cylindrical hole. This can be seen in Figure 4b. The separation remains almost constant for the first two diameters in the laterally diffused case, and then begins to decrease by 3.5 diameters. The structures associated with the cylindrical hole, have a constant separation for the entire 3.5D region that was studied. The pinching together of the vortices for the laterally diffused geometry is most likely caused by a stronger shear layer generated with the mean flow since the diffused streamwise flow is less than for the cylindrical hole.

The effects on the surface coverage for each geometry at a compound angle of 90° is shown in Figure 5. The cylindrical and forward diffused cases provide jet contact with the surface for the entire span of 3 and 4.5 diameters, respectively. The laterally diffused hole, on the other hand, covers nearly two thirds of the span between adjacent jets. This is most likely caused by the lower momentum fluid in the transverse direction from the laterally diffused jet. Due to the lower momentum, the mainstream is able to deflect the jet easier, thus preventing complete surface coverage. The centers of the flow structures for the laterally diffused geometry also have greater elevation from the surface than either of the other two hole geometries. This indicates greater lift, with the undesired consequence of increased mainstream fluid drawn underneath the jet core, and thereby heating the surface.

Figure 6 shows the effects of compound angle on jet penetration distance for the laterally diffused hole geometry. All three angles show increasing penetration as the compound angle increases. A peak occurs between 1 and 2 diameters downstream of the holes, followed by a gradual decrease in penetration distance. The vertical momentum of the jet increases with compound angle due to two effects, one is an increased obstruction of the flow for a row of jets, and the other is an increase in aerodynamic lift as the mainstream flow is deflected over the circulating jet core for larger compound angle.

Figure 7 shows a representative plot of streamwise aligned vorticity at x/D = 0 for the streamwise injected, cylindrical hole. There exists two counter rotating vortices. The shaded areas on the right represent negative vorticity (counterclockwise being positive) and the shaded areas on the left show positive vorticity. One can also see that peak magnitudes of vorticity are present near the centers of each vortex, as expected. The magnitudes for the counterclockwise and the clockwise vortices are approximately the same at 3.1x10³ 1/s. Similar plots were obtained for all downstream test locations and geometries.

Figure 8a shows the peak vorticity versus x/D for the cylindrical hole cases. The streamwise vorticity shows a decided increase as compound angle increases. This is caused by alignment of the jet momentum with the transverse direction as the compound angle increases and thereby increasing the strength of the cross stream flow components. The vorticity is further enhanced by interaction with the mainstream flow as it is deflected over the circulating injected fluid.

Figure 8b shows the peak vorticity for the three laterally diffused cases and the forward diffused. The forward diffused case has the lowest levels of vorticity. This is due to the lower transverse velocities caused by diffusion in the transverse direction. This results in lower overall momentum and, subsequently, lower vorticity. The velocity vectors for the forward diffused case, in Figure 3c, shows the lack of a well defined vortex. Instead, there is a large asymmetric rotating flow field. Consequently the streamwise aligned vorticity is lower for this case. This does not preclude the existence of other components of high vorticity.

The peak vorticity for the lateral diffused and the circular holes at 0° compound angles is shown in Figure 9a. Vorticity levels for the laterally diffused case remain nearly constant, at values greater than those for the cylindrical case. This may be a result of lateral diffusion causing higher momentum in the transverse direction, and thus, higher vorticity magnitudes or the fact that the laterally diffused cases tend to have higher momentum concentrated near the surface resulting in higher maintained vorticity in the surface region.

Comparison of peak vorticity for all three geometries, for 90° compound angle, are shown in Figure 9b. The forward diffused case has the lowest streamwise-aligned vorticity and the cylindrical hole has the highest. This is contrary to the results for 0° compound angle, and is a consequence of the cylindrical hole having the greatest momentum in the transverse direction. The maximum vorticity does not necessarily decrease downstream in the near hole region. The vorticity strength increases for the cylindrical case due to the entrainment of the mainstream fluid under the jet core at 0° compound angle. This effect is reduced for the other geometries and at nonzero compound angle.

These results illustrate a number of effects of hole geometry and orientation applied to film cooling. First, as the compound angle is increased, the pair of counter-rotating vortices present in the jet core decay into a single, recirculating structure. This occurs because within the vortex pair, the upstream vortex is destroyed by interaction with the crossflow. Second, the flow structures increase in size but decrease in strength as the flow develops downstream. This confirms the expected behavior of the jet caused by entrainment and decay of momentum aligned perpendicular to the mainstream direction. Third, increases in compound angle cause subsequent increases in penetration distance of the jet into the mainstream. This is due mainly to changing of the streamwise aligned momentum to spanwise aligned momentum. This causes each jet to interact with its neighbor. Fourth, the present of a lift force, generated by the mainstream fluid shear over the jet core, causes a low pressure region. These last two effects combine to cause the jet to move away from the surface.
CONCLUSIONS

The use of PIV has been demonstrated to be a useful tool to illustrate the lateral flow filed characteristics for jet-crossflow interactions and to be able to discern the flow characteristics for different jet hole geometries and orientations. Very large variations in the lateral flow field has been observed showing unique vorticity distributions resulting from different exit hole geometries and compound angles. Based on these results the laterally diffused hole geometry without compound angle provides the best coverage in the near hole region. This geometry is shown to generate flow structures that are well separated and close to the test surface. The lateral diffusion also provides lower exit momentum, thus causing the interaction with the mainstream to have less penetration of the jet core. Unique vorticity distributions for the different geometries and compound angles contribute to the potential improvements in heat transfer performance.

REFERENCES


(a) Cylindrical Hole
(b) Laterally Diffused Hole
(c) Forward Diffused Hole

Figure 1. Schematic Representation of Film Hole Geometries Studied.
Figure 2. Velocity: Cylindrical Shaped Holes (a) $\alpha = 0^\circ$, $x/D = 0$, (b) $\alpha = 0^\circ$, $x/D = 2$, (c) $\alpha = 90^\circ$, $x/D = 2$.

Figure 3. Velocity: Laterally and Forward Diffused Holes (a) LDIF, $\alpha = 0^\circ$, $x/D = 1$, (b) LDIF, $\alpha = 90^\circ$, $x/D = 1$.

Figure 4. Effect of Hole Geometry On: (a) Surface Coverage Width, (b) Structure Separation Distance, $\alpha = 0^\circ$.

Figure 5. Effect of Hole Geometry on Surface Coverage Width, $\alpha = 90^\circ$. 
Figure 6. Effect of Compound Angle on Laterally Diffused Hole (a) Jet Penetration Distance, (b) Major Structure Elevation.

Figure 7. Representative Plot of Streamwise Aligned Vorticity: Cylindrical Hole, $\alpha = 0^\circ$, $x/D = 0$.

Figure 8. Effect of Compound Angle on Streamwise Vorticity. (a) Cylindrical Hole, (b) Laterally and Forward Diffused Holes.

Figure 9. Effect of Hole Geometry on Streamwise Vorticity (a) $\alpha = 0^\circ$, (b) $\alpha = 90^\circ$. 