Influence of flow injection angle on a leading-edge horseshoe vortex

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Abstract

Junction flows that develop at the base of protruding obstructions occur in many applications. An unsteady horseshoe vortex is formed as a component of these junction flows, which increases the local heat transfer on the associated endwall. Augmenting this junction flow can be achieved through the injection of fluid upstream of the obstruction. This experimental study evaluated the effects of injection angle for a two-dimensional slot placed upstream of a vane leading-edge with four injection angles of 90°, 65°, 45°, and 30°. Results showed that high momentum injection increased the endwall heat transfer at each slot angle while low momentum injection resulted in a relatively lower augmentation of endwall heat transfer. A leading-edge vortex turning into the endwall was formed at the junction in the stagnation plane for high momentum injection at 90° and 65° while a leading-edge vortex turning away from the wall was formed for 45° and 30° injection. For low momentum injection, a vortex turning into the endwall was formed at all injection angles.

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1. Introduction

The use of obstructions protruding from an endwall into a crossflow has applications ranging from internal cooling channels to external turbine airfoils. The particular shape of the obstruction can vary widely between different applications. A common geometry among many protruding features, however, is the junction of a rounded leading-edge obstruction as in the case of a pin fin within a channel or a nozzle guide vane in a gas turbine engine. As the approaching velocity boundary stagnates onto the obstruction, a leading-edge vortex is formed. The leading-edge vortex, commonly referred to as the horseshoe vortex (HSV) converges around the obstruction increasing the heat transfer on the endwall at the junction [1–2]. The particular dynamics of the HSV is dependent on several parameters such as Reynolds number, boundary layer characteristics, turbulence level, and leading-edge diameter [3–7]. The collective conclusion from past studies, however, is that the HSV is an unsteady structure that is responsible for high turbulence intensities, subsequently leading to high heat transfer at the junction. While an increase in heat transfer is desired for a pin fin within a cooling channel, an increase in heat transfer for a gas turbine airfoil can be detrimental to the component life.

One method of augmenting the heat transfer on the endwall in the junction region is by altering the leading-edge flowfield and the subsequent formation of the HSV by injection flow through the endwall upstream of the obstruction. An important parameter influencing the effects of the injecting flow is the angle of injection relative to the endwall. While several past studies have indicated that flow injection upstream of a vane can augment the junction region heat transfer and flowfield, very few studies have investigated the effects of injection angle [8–14].

An experimental study by Rehder and Dannhäuser [15] utilized an axisymmetric contoured blade passage to investigate the effects of tangential and perpendicular slot injection. Flowfield measurements indicated that tangential injection with an injection mass flow rate of 2% and injection momentum flux ratio of 1.6 energized the approaching boundary layer leading to a reduction of the secondary flows. In contrast, perpendicular injection led to a more turbulent flowfield within the passage that was observed with no injection indicating that the passage vortex was distributed over a larger area of the flowfield. Though similar in peak value, high heat transfer values on the endwall were shown to extend further into the blade passage when fluid was injected perpendicular to the endwall as compared to tangential. For low mass flow rate injection at 1% associated with a momentum flux ratio of 0.4, no distinct changes to the secondary flows or endwall heat transfer was observed.

The only other available study to investigate the effects of injection slot angle on heat transfer was performed by Thrift et al. [16] using the same flow conditions and injection angles as the study reported in this paper, but with only time-averaged measurements. The focus by Thrift et al. [16] was on thermal measurements within the vane passage and time-averaged flowfield measurements in the stagnation plane. In comparison to the study by Rehder and Dannhäuser [15], a higher momentum flux ratio of 2.8 was used with a lower mass flow rate of 1%. Results indicated
the formation of a large, leading-edge vortex for high momentum injection at 65° or greater which led to high endwall heat transfer. For high momentum injection at 45° or less, however, the injecting flow did not separate, eliminating the formation of the time-averaged HSV and weakening the subsequent passage secondary flows. Unfortunately, passage heat transfer was still high for injection at high momentum at 45° or less. Reducing the injection momentum flux to 0.7 with a mass flow rate of 0.5% resulted in lower passage heat transfer levels than that observed for high momentum injection for each injection angle.

The emphasis of the investigation reported in this paper is on the endwall heat transfer and stagnation plane flowfield at the junction of a rounded, leading-edge vane and flat endwall with varying injection slot angles and injection flow rates. This work expands on the previously mentioned studies by providing analysis of the time-resolved junction flowfields for each injection angle and injection flow rate. Furthermore, results are also presented for the case of no injection slot to serve as a baseline for comparison.

2. Experimental facility

All experiments were conducted in a low-speed, closed-loop wind tunnel facility depicted in Fig. 1 and previously described by Thrift et al. [16]. Driving the flow through the wind tunnel was a variable speed fan. Downstream of the fan, the flow was turned by a 90° elbow before being passed through the primary, finned-tube heat exchanger used to remove the heat supplied to the flow by the fan. After being turned by another 90° elbow, the air was split into three flow paths. The flow which passed through the upper and lower passages entered into respective plenums and could be used as injection fluid while flow passing through the center passage served as the mainstream flow. A fraction of the flow was drawn from the upper plenum only and into a plenum that supplied the injectant to the slot using a variable speed blower.

During all experiments the mainstream and injection flows were maintained at a constant temperature at 25 °C to ensure that the heat transfer coefficients were reported for one driving temperature, wall minus freestream as indicated in the nomenclature. Downstream of the flow split, the mainstream passed through a series of screens used for flow straightening, and then into a contracted straight flow section with a rounded inlet. At the exit of the straight flow section was the experimental test section where all measurements were performed. The test section incorporated a linear vane cascade. Air exiting the test section was turned by a final 90° elbow before encountering the fan and completing the closed-loop.

The test section consisted of a two-dimensional, linear vane cascade as illustrated in an over-head schematic in Fig. 2. The two passage cascade contained two full nozzle guide vanes and a third partial vane connected to a flexible wall. The vane design was a vertical extrusion of a two-dimensional midspan geometry. A description of the vane parameters and the freestream flow conditions are given in Table 1. Note that the freestream turbulence intensity was maintained at 1.0% for this study. Table 1 lists an effective diameter of the vane leading-edge which was determined by matching the predicted inviscid approach velocity within the stagnation plane of the vane to the inviscid approach velocity within the stagnation plane of a circular cylinder [17].

The inlet velocity was measured 3.7d_{eff} upstream of the vane cascade and was found to vary less than 5% from the pitch averaged mean for all experiments. Static pressure measurement were made around the circumference of each vane at midspan and compared with predictions. As shown previously by Thrift et al. [18], the measured and predicted pressure distributions agreed indicating that the inviscid flowfield around each vane was matched to the predicted curve. The boundary layer entering the cascade was measured at a location 9.6d_{eff} upstream of the vane leading-edge.

![Fig. 1. Depiction of the low speed, closed loop wind tunnel.](Image)
Table 2 lists the turbulent inlet boundary layer parameters, which were maintained throughout this study.

The two-dimensional slot was placed upstream of the vane cascade as illustrated in Fig. 2. Also shown in Fig. 2 are the four slot injection angles of 90°, 65°, 45°, and 30° that were investigated. Each slot had a flow length-to-width of 11.7. The downstream edge of each slot was located 0.39d_eff upstream from the geometric stagnation location of the vane. The temperature of the injecting flow was measured using three thermocouples located within the slot plenum. The recorded plenum temperatures were found to vary less than 0.5°C from the average injection fluid temperature for all experiments.

High and low average momentum flux ratios, I = 2.8 and 0.7, were investigated. The flow exiting the slot was highly non-uniform resulting from the effects of the static pressure variation from the vane and as such, average momentum flux ratios are reported. The average momentum flux ratio was calculated according to the equation in the nomenclature. The total mass flux issuing from the upstream leakage slot was measured using a laminar flow element located within the supply pipe to the slot plenum. A mass flux ratio (MFR) was defined as the ratio of injectant issuing from the upstream slot and entering a single passage to the mainstream mass flow rate through a single passage. With a fixed slot width of w = 3.3 mm (0.033d_eff) an average momentum flux ratio of I = 2.8 was calculated corresponding to MFR = 1.0%. The low momentum flux ratio condition of I = 0.7 was achieved by lowering the mass flux ratio with the given slot width to MFR = 0.5%.

2.1. Measurement methods

For the results presented in this paper, heat transfer coefficients on the endwall at the junction were measured. In addition,
time-resolved flowfield measurements were also performed in the junction region within the stagnation plane. Heat transfer measurements were made by capturing steady state endwall temperatures using an Infrared (IR) camera with a constant heat flux boundary condition on the endwall. The constant heat flux surface was achieved with a thin heater permanently bonded to a low thermal conductivity foam plate to reduce conduction losses to the external environment. The heater covered the entire endwall, from immediately downstream of the slot to the trailing edge of the second full vane as shown by the heater outline in Fig. 2.

Two thermocouples embedded in the endwall surface were located in the IR picture to calibrate each image. Typical emissivity and background temperature values after calibration were in the range of 0.93–0.96 and 25 °C–30 °C respectively. The background temperature corresponded to the approximate mainstream temperature of the flow as the surrounding environment was allowed to reach steady state. In calculating the heat transfer coefficient, the total power supplied to the heater was corrected to account for conduction and radiation losses. The percentage of the radiation heat flux loss was typically between 3–16% of the total supplied heat flux. The percentage of conduction heat flux loss was typically between 0.5–1.0%.

Flowfield measurements were made in the stagnation plane of the center vane using high-image-density, time-resolved, digital particle image velocimetry (TRDPIV). TRDPIV is a non-intrusive, indirect, whole field, laser-optical measurement technique based on the illumination and tracking of groups of particles which follow the flowfield [19–23]. For the TRDPIV technique used in this study, a double frame of images was captured over a short time period using a high speed CMOS camera and a high frequency, double pulsed laser to illuminate the seeder particles. As shown in Fig. 2 the laser sheet was located over the center vane. Flowfields were captured using a camera sampling frequency of 1 kHz for 3 s resulting in the recording of 3000 image pairs. The sampling frequency and sampling duration were chosen based on the characteristic fluid time scale, \( s_f \), as defined in the nomenclature. A sampling frequency and sampling duration of 1 kHz and 3 s corresponded to 12 \( s_f \) and 250 \( s_f \) respectively ensuring that the flow features were temporally resolved. Once captured, images were processed using commercially available software [24]. As indicated in Fig. 2 the camera was at a slight angle to the stagnation plane, typically less than 8°. Using the software, the adjusted raw images were also corrected for the small off normal viewing angle. A viewing angle of 8° results in a less than 1% correction in the streamwise velocities. After correction, the images were processed using a decreasing, multi-pass technique to determine the displacement vectors. The multi-pass scheme employed a single pass at an interrogation window size of 32 × 32 pixels followed by two passes at an interrogation window size of 16 × 16 pixels with 50% overlap resulting in a final vector spacing of 8 × 8 pixels. The displacement vectors were calculated for each interrogation window amongst image pairs using a standard cross-correlation, cyclic FFT-based algorithm. Vector validation was performed after each pass using a 4-pass regional median filter with adjustable criteria for the removal and re-insertion of possible spurious vectors.

2.2. Measurement uncertainties

An uncertainty analysis was performed on the measurements of heat transfer using the partial derivative method described by Moffat [25]. Uncertainty in Stanton numbers was dominated by the uncertainty in surface temperature measurements. For those measurements, a precision uncertainty of approximately ±0.2 °C was estimated from the standard deviation of the five IR images measurements based on a 95% confidence interval. The bias uncertainty was taken as the root-sum-square of the thermocouple bias uncertainty (±0.2 °C) and the average deviation of the calibrated images from the thermocouples (±0.5 °C) resulting in a bias uncertainty of ±0.54 °C. Combining the bias and precision uncertainties, a total uncertainty in Stanton number was found to be \( \Delta St = ±0.0005 \).
(5%) at \(St = 0.01\) and \(\partial St = \pm 0.0018\) (9%) at \(St = 0.02\). Note that higher uncertainties are associated with higher Stanton numbers due to smaller temperature differences between the mainstream and heater surface.

Uncertainty in the TRDPIV velocity measurements was calculated based on the average particle displacement, maximum displacement gradient, average particle image density, and signal-to-noise ratio \[19, 26\]. The uncertainty in the instantaneous velocity measurement was found to be approximately \(\partial U = 0.16\) m/s (2% of \(U_1\)) for a bulk particle displacement of 8 pixels. Expanding the instantaneous velocity uncertainty to the turbulence intensity as defined in the nomenclature based on the partial derivative method, an uncertainty in turbulence intensity was calculated to be \(\partial Tu = \pm 0.02\) for \(Tu = 0.1\) to 0.4.

\[3. Time-averaged results\]

Baseline conditions without an injection slot were measured to compare to those results with injection upstream of the vane leading-edge. Fig. 3(a–e) presents the contours of Stanton number on the endwall in the junction region. For the baseline condition shown in Fig. 3a, near the upstream edge of the heater, located 0.39\(d_{eff}\) from the vane stagnation, the endwall heat transfer shows the effects of an unheated starting length. At the stagnation, however, an expected increase in the endwall heat transfer is observed as a result of the junction flow.

To compare the heat transfer measurements with previously published data, Fig. 4 gives the augmentation of the endwall heat transfer for both circular cylinders and leading-edge vane geometries with no upstream injection slot present. For the cylindrical data, the endwall heat transfer augmentation is calculated using the heat transfer coefficients along the stagnation line approaching the leading-edge divided by the Stanton numbers along the same streamwise position but with no cylinder present. For the vanes, the heat transfer augmentation is calculated by dividing the heat transfer coefficients along the stagnation line by those along the midpitch line to minimize the influence from the vanes. Concerning the vane data, Fig. 4 indicates fairly good agreement in endwall heat transfer between the studies. Away from the stagnation the

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**Fig. 6.** Comparison of time-averaged flowfield vectors with overlaid streamlines and contours of turbulence intensity in the stagnation plane for injection angles of (a) 90°, (b) 65°, (c) 45°, and (d) 30° to the respective endwall heat transfer along the stagnation line for injection angles of (e) 90°, (f) 65°, (g) 45°, and (h) 30° with \(r = 2.8\) and MFR = 1.0%.
The flow is reversed towards the upstream along the endwall resulting in the formation of a time-averaged HSV as shown in Fig. 5a. Fig. 5b presents the associated line plot of endwall heat transfer along the stagnation line which is highlighted in Fig. 3a. The stagnation line heat transfer shows an increase near the stagnation which coincides with the impingement of the mainstream flow as indicated by the streamlines. In addition to the high turbulence levels generated by the HSV, Fig. 5a indicates the time-averaged separation or saddle point where the near wall flow begins to reverse upstream at approximately $x/d_{eff} = -0.35$. The time-averaged separation location of the impinging boundary layer agrees well with past studies for circular cylinder and symmetric airfoil type junction flows which collectively report a separation location in the range of $0.3 < |x/d_{eff}| < 0.5$ [30–36].

3.1. Effects of slot angle for high momentum injection

To determine the effects of high momentum slot injection on the heat transfer and flowfield in the leading-edge region, high momentum air ($I = 2.8$, $MFR = 1.0\%$) was injected upstream of the vanes through a two-dimensional slot over a range of injection angles. Fig. 3(b–e) present contours of Stanton number on the endwall at the junction for injection angles of 90°, 65°, 45°, and 30°. In comparison to the baseline case with no injection slot in Fig. 3a, high momentum injection for each slot angle results in a substantial increase in endwall heat transfer. Concerning the cases with injection, there is a fundamental difference in the distribution of endwall heat transfer between the 90° and 65° slots as compared with the 45° and 30° slots respectively. For high momentum injection at 90° and 65° the endwall heat transfer near the stagnation is similar between the two injection angles and higher than that observed for the 45° and 30° slots. Upstream of the stagnation, however, endwall heat transfer is higher for the 65° slot in comparison to the 90° slot. In contrast, near the exit of the injection slot the endwall heat transfer for the 45° and 30° slots is similar and higher than that observed for the 90° and 65° slots.

To understand the differences in endwall heat transfer, Fig. 6(a–d) present the time-averaged flowfields with streamlines overlaid with contours of turbulence intensity in the stagnation plane of the vane for injection angles of 90°, 65°, 45°, and 30°. Below each flowfield, Fig. 6(e–h) present the respective endwall heat transfer along the stagnation line in comparison to the baseline case for injection angles of 90°, 65°, 45°, and 30°. In comparison to having no injection slot, high momentum injection at 90° and 65° results in the formation of a much larger HSV while injection at 45° and 30° shows an absence of a HSV. The strong shear layer and the subsequent high turbulence levels resulting from injecting high momentum fluid along the endwall for the 45° and 30° slots are also shown to provide high heat transfer. Regardless, for each slot angle with high momentum injection, turbulence levels are above that observed with no injection and the heat transfer along the stagnation line is also higher than the baseline.

A reduction in the injected flow penetration depth and a subsequent reduction in the size of the time-averaged vortex are evident in comparing the 90° and 65° slots. A comparison of Fig. 6(a) and (b) shows that the center of the time-averaged vortex forms closer to the endwall for the 65° slot. The addition of a streamwise injection component for the 65° slot as compared to the 90° slot also drives the vortex closer to the vane stagnation. Injection at 65° results in higher turbulence levels than that observed for the 90° slot thereby giving higher endwall heat transfer. Note that a small secondary vortex forms upstream of the fluid injected at 90° as a result of the physical blockage to the approaching boundary layer for the injection. For 65° injection, the measurements do not indicate a resolvable secondary vortex upstream of the injection. In contrast to the 90° and 65° injection cases, 45° and 30° injection

Fig. 7. Endwall heat transfer in the junction region (a) with no injection slot and for injection angles of (b) 90°, (c) 65°, (d) 45°, and (e) 30° with $I = 0.7$ and $MFR = 0.5\%$.
has a much stronger streamwise component. The stronger streamwise component results in the high momentum fluid being injected along the endwall where it convects upward along the surface of the vane eliminating the downwash and subsequent impingement of the boundary layer flow onto the endwall. As a result of this differing flow pattern, the endwall heat transfer at the vane stagnation is lower in the case of the 45° and 30° slots relative to the 90° and 65° slots where downwash is present. Note that stronger upwash as a result of an increased streamwise injection component for the 30° slot in comparison to the 45° slot results in the regular formation of a small counter-clockwise (CCW) rotating vortex on the vane surface. At the exit of the injection slot for the 90° and 65° slots there is a small, low velocity region between the injecting flow and the vortex. As a result of the higher velocities in the 45° and 30° slot cases, there is an increase in the heat transfer near the exit of the injection slot relative to the 90° and 65° slots.

3.2. Effects of slot angle for low momentum injection

In addition to high momentum injection upstream of the vane, experiments were also conducted at a low momentum flux ratio ($I = 0.7$, MFR = 0.5%). Fig. 7(a–e) present contours of Stanton number on the endwall at the junction for the baseline case and for injection angles of 90°, 65°, 45°, and 30° at the reduced momentum flux ratio. The general distribution of endwall heat transfer that was observed for the baseline case and high momentum injection cases persists for reduced momentum injection. That is, the endwall heat transfer is initially high at the exit of the injection slot in comparison to the 45° slot results in the regular formation of a small counter-clockwise (CCW) rotating vortex on the vane surface. At the exit of the injection slot for the 90° and 65° slots there is a small, low velocity region between the injecting flow and the vortex. As a result of the higher velocities in the 45° and 30° slot cases, there is an increase in the heat transfer near the exit of the injection slot relative to the 90° and 65° slots.

Fig. 8. Comparison of time-averaged flowfield vectors with overlaid streamlines and contours of turbulence intensity in the stagnation plane for injection angles of (a) 90°, (b) 65°, (c) 45°, and (d) 30° to the respective endwall heat transfer along the stagnation line for injection angles of (e) 90°, (f) 65°, (g) 45°, and (h) 30° with $I = 0.7$ and MFR = 0.5%.
To understand the similarities in heat transfer between low momentum injection and the case without an injection slot present, the stagnation plane flowfields accompanied with the respective endwall heat transfer along the stagnation line are presented in Fig. 8(a–h) for the reduced momentum flux ratio. In contrast to high momentum injection, low momentum injection results in the formation of an HSV for each injection angle. Low momentum injection at 90° and 65° results in the formation of a time-averaged vortex that is of the same approximate size, location, and turbulence level as that for the baseline case. For injection at 45° and 30°, a smaller time-averaged vortex is formed at the corner of the junction that also produces turbulence levels in the same range as those observed in the baseline. The presence of an HSV and the associated turbulence drive the endwall heat transfer in the junction region thus the heat transfer levels and distributions are similar between low momentum injection at each slot angle and the case with no injection slot.

Comparing to the flowfields shown previously for high momentum injection, the leading edge vortex that forms for 90° injection is much larger and results in higher turbulence levels than that observed for the reduced momentum flux case. For 90° injection, the leading-edge vortex that forms for each momentum flux ratio case is centered at $x/d_{eff} = -0.25$. This is expected as each momentum flux ratio condition is under the influence of the same mainstream Reynolds number and boundary layer. There is a reduction in the vertical position of the vortex core for the 90° slot, however, with a reduction in momentum flux. The vortex formed for low momentum injection at 65° also maintains the same streamwise location as the high momentum flux case. At both momentum flux ratios the vortex formed from 65° injection maintains the same vertical position for low momentum injection at 45° and 30° the velocity deficit within the approaching boundary layer is not fully energized thereby resulting in the HSV. In comparison to the baseline case, the HSV formed for low momentum injection at 45° and 30° is pushed closer to the vane stagnation.

In general, low momentum injection results in weaker turbulence levels and lower endwall heat transfer in the junction region for all four slot angles in comparison to the high momentum injection. At high momentum injection, the slot-averaged injection velocity is approximately 70% higher than the freestream velocity. Consequently, the large velocity difference between the injecting fluid and near wall flow leads to large separation regions for the 90° and 65° slots and strong shear layers for the 45° and 30° slots respectively. With low momentum injection, however, the slot-averaged injection velocity is approximately 17% lower than the freestream. The smaller velocity disparity between the injecting fluid and near wall flow for injection at low momentum results in smaller separation regions and weaker shear layers thereby reducing the stagnation plane turbulence for each slot angle in...
comparison to high momentum injection. As a result of the reduced turbulence levels, the endwall heat transfer at the junction for low momentum injection compared to high momentum injection is lower for each slot angle.

4. Time-resolved flowfield results

The particular dynamics of the HSV has been measured by the current authors [27,28] for external and internal flows as well as by Praisner and Smith [29] using time-resolved, PIV. In these past studies, the HSV was characterized as having a bimodal flow pattern as the outer wall fluid impinged at stagnation, turned upstream, and interacted with the near wall fluid of the approaching boundary layer. Fig. 9(a) and (b) present instantaneous flowfields with no injection. As identified by the structure of the flowfield, in the first mode the reverse near wall flow passes under the HSV and travels upstream over a small secondary vortex, which may or may not be present, to eventually sweep into a tertiary vortex. The first mode persists until it is interrupted by a quasi-periodic switching to a second mode. In the second mode, the reverse near wall flow stops passing in to the tertiary vortex as the outer wall fluid penetrates to the endwall surface behind the HSV forcing the structure further upstream. The oblong shaped distribution of the high turbulence contours shown in Fig. 5a about the time-averaged position of the vortex core highlights the movement of the HSV during the quasi-periodic switching between flow modes.

4.1. Effects of slot angle for high momentum injection

To quantify the instantaneous strength of the vortices for the various injection conditions, Fig. 10(a–d) present contours of probability density function (PDF), as defined in the nomenclature, based on swirling strength that isolates rotation within a flowfield. Swirling strength is defined as the positive imaginary component of the complex eigenvalue of the local two-dimensional, velocity-gradient tensor. The PDF contours were generated using a threshold for swirling strength based on the inverse square of the time required for the high momentum injectant to reach the leading-edge of the vane along the streamwise direction. The swirling strength threshold, as defined in the nomenclature, was found to provide an accurate representation of the time-resolved, rotational nature of the flowfield. Changing the threshold criteria by an order of magnitude did not result in the discovery or elimination of any time-resolved features among injection cases. Only the scale of the PDF was altered by changing the threshold criteria.

As shown in Fig. 10b, high momentum injection at 90° results in a high PDF level with a uni-modal distribution centered on the time-averaged position of the vortex as shown in Fig. 6a. The high PDF level for injection at 90° highlights the strength of the instantaneous vortex in comparison to the baseline case in Fig. 10a where PDF levels are substantially lower and are distributed in an oblong pattern. Fig. 10c indicates that injection at 65° generally results in a weaker vortex than that observed for 90° injection as the peak PDF level is lower. Similar to the 90° slot, however, PDF levels for 65° injection are substantially higher than in the baseline case. Fig. 10c also shows the infrequent production of a secondary vortex upstream of the 65° injecting coolant which was not resolved in the time-average.

To investigate the stability of the vortices, Fig. 11(a–d) present histogram contours of streamwise velocity in the stagnation plane with the overlaid time-averaged velocity profiles for (a) the baseline case with no injection and for injection angles of (b) 90°, (c) 65° and (d) 30° with $I = 2.8$ and MFR = 1.0%.
Fig. 11(a–c) the presence of the clock-wise rotating vortex is evident in the positive streamwise velocities far from the endwall and negative velocities close to the endwall. As expected, the largest peak velocities are associated with high momentum injection at $90^\circ/C_{176}$ while the smallest peak velocities are associated with the baseline case. The range of streamwise velocities for high momentum injection at $90^\circ/C_{176}$ is similar to those of the baseline case indicating the relative stability of the large vortex. High momentum injection at $90^\circ/C_{176}$ washes the boundary layer flow into the mainstream allowing the instantaneous vortex to remain stable.

For high momentum injection at $65^\circ/C_{176}$ shown in Fig. 10c, however, the instantaneous vortex exhibits a more unsteady nature than that observed for both $90^\circ$ injection and the baseline case. For $65^\circ$ injection, the approaching boundary layer flow is able to frequently disrupt the injecting fluid leading to substantial fluctuation and distortion of the instantaneous vortex. As shown in Fig. 11c, the range of instantaneous velocities observed for $65^\circ$ injection is much larger than that shown for both injection at $90^\circ$ and the baseline case. A relatively unsteady vortex for high momentum injection at $65^\circ$ results in the higher peak turbulence levels that were shown previously in Fig. 6b.

To provide further evidence of the time-resolved dynamics of the vortex produced by $65^\circ$ injection, Fig. 12(a–c) present several instantaneous flowfields in the stagnation plane of the vane. Typically, the injecting flow is oriented at approximately $65^\circ$ as shown in Fig. 12a resulting in the formation of a fairly circular vortex. Intermittently, the approaching boundary layer flow is able to disrupt the vertical penetration depth and angle of the injectant, forcing the vortex closer to the endwall and translating the distorted structure further downstream. Fig. 12(a–c) indicate that the boundary layer flow is able to frequently rush into the region just downstream of the vortex and the vane. The time-averaged result of the turning of boundary layer streamlines into the region near the vane stagnation is higher turbulence levels for $65^\circ$ injection in comparison to the $90^\circ$ slot as shown previously in Fig. 6.

In contrast to the time-averaged results in Fig. 6c, Fig. 10c captures the production of a secondary vortex on the vane surface along the stagnation line for injection at $30^\circ$ at a height of $z/S = 0.22$. Note that injection at $30^\circ$ results in a very similar PDF distribution to that shown for the $45^\circ$ slot and is therefore not presented. Stronger upwash in the case of high momentum injection at $30^\circ$, however, produces larger vertical velocities on the vane stagnation resulting in earlier separation. Earlier separation on
the vane stagnation for injection at $30^\circ$ results in a vortex on the surface of the vane that is located closer to the endwall than that observed for $45^\circ$ injection as shown previously in Fig. 6d. A comparison of Figs. 6c and 10c for the $45^\circ$ slot shows that high PDF contours are effectively bounded by the time-averaged inflection points of the velocity. The inflection points indicate the shear layer below which the injecting fluid undergoes a strong interaction with the boundary layer flow. Upwash at the corner of the junction leads to a frequent production of high swirling strength. A turning of the near wall flow toward midspan results in the formation of strong CCW rotating vortices near the corner of the junction.

Although weaker in strength than the intermittent vortices formed near the corner of the junction, CCW rotating vortices also form along the inflection points in the time-averaged streamlines for injection at both $45^\circ$ and $30^\circ$. Fig. 13(a–c) present instantaneous flowfields in the stagnation plane of the vane for high momentum injection at $30^\circ$ indicating the formation of small CCW rotating vortices. The intermittent vortices that form convect along the shear layer and up the surface of the vane to either conglomerate into the vortex that is present on the vane surface or move out of the stagnation plane. In addition to the intermittent vortices, the instantaneous flowfields indicate a strong upwash along the vane surface acts as impedance to the approaching boundary layer moving the subsequent downwash further upstream. As a result, the boundary layer flow is driven into the shear layer often disrupting the strong streamwise flow along the endwall. The disruption to the near wall flow either results in a compression of the near wall streamlines or a small separation region as shown in Fig. 13c.

While the high momentum injectant is able to remain attached to the endwall for the $45^\circ$ and $30^\circ$ slots, the magnitude of the streamwise velocities are subject to substantial fluctuation as a result of the disturbances caused by the intermittent vortices and downwash. Fig. 11d presents a histogram of the streamwise velocity for the $30^\circ$ slot along a vertical profile located at $x/d_{eff} = -0.23$ corresponding to the midpoint between the time-averaged vortices that was evident for the $90^\circ$ and $65^\circ$ cases. Although confined near the endwall, the spreading of streamwise velocities is similar to that shown for the $65^\circ$ slot resulting in similar peak turbulence levels. Note that the spreading of streamwise velocities for the $45^\circ$ slot was only slightly less than that shown for the $30^\circ$ slot with the average peak velocity being lower as a result of a weaker streamwise injection component for the $45^\circ$ slot.

**Fig. 14.** Probability density function contours of swirling strength for a threshold of $(U_i/0.39d_{eff})^2$ in the stagnation plane for injection angles of (a) $90^\circ$, (b) $65^\circ$ and (c) $45^\circ$ with $I = 0.7$ and MFR = 0.5%.

**Fig. 15.** Instantaneous flowfield vectors with overlaid streamlines in the stagnation plane showing the dissipation of a small secondary vortex formed between the injecting fluid and the primary vortex for injection at $65^\circ$ with $I = 0.7$ and MFR = 0.5%.
4.2. Effects of slot angle for low momentum injection

For low momentum injection, Fig. 14(a–c) present PDF contours of swirling strength for injection angles of 90°, 65°, and 45° using the same threshold criteria as in Fig. 10 for high momentum injection for comparison. Similar to high momentum injection at 90°, a unimodal distribution is observed for low momentum injection at 90° although peak PDF levels are lower indicating a weaker instantaneous vortex. Fig. 14a also shows the infrequent production of a small secondary vortex upstream of the 90° slot that was not evident in the time-averaged results. Similar to that seen for high momentum injection, reducing the injection angle to 65° results in a reduction in peak PDF level in comparison to low momentum injection at 90° as shown in Fig. 14b. A secondary peak in PDF level downstream of the 65° slot highlights the intermittent formation of a small secondary vortex between the injecting fluid and the primary vortex. A large distance between slot and vortex in addition to a weak instantaneous vortex for low momentum injection at 65° allows for the frequent formation of a small secondary vortex.
Fig. 15(a–c) present instantaneous flowfields indicating the formation and dissipation of the secondary vortex for low momentum injection at 65°. When present, the secondary vortex is moved downstream by the injecting fluid where it is dissipated by the primary vortex as the two structures rotate in opposing directions. The existence of the secondary vortex, however, does not result in a significant displacement of the primary vortex.

Fig. 16(a–c) present histogram contours of the streamwise velocities along vertical profiles for low momentum injection at 90°, 65° and 30°. Note that for Fig. 16(a) and (b) the vertical profiles are located at a streamwise position corresponding to the center of the time-averaged vortices. Similar to high momentum injection, low momentum injection at 90° results in a range of streamwise velocities that is very similar to the baseline case. In contrast to high momentum injection at 65°, however, the range of streamwise velocities is small and in the same range as that observed for the baseline case and injection at 90° for low momentum injection at 65°.

The PDF contours of swirling strength in the stagnation plane for low momentum injection are very similar between the 45° and 30° slots. As such Fig. 14c presents only the contour for low momentum injection at 45°. As expected the peak PDF value is concentrated at the corner of the junction where the time-averaged results indicate the regular formation of a small vortex. The interaction between the downwash and the flow injected along the endwall, however, often results in the removal of the corner vortex for the 45° and 30° slots. Fig. 17(a–d) present instantaneous flowfields for low momentum injection at 30° showing how the corner vortex is reduced in size by the downwash to the point where the structure is removed.

Further upstream from the corner vortex, the endwall flow remains relatively stable as shown in Fig. 16c which presents a PDF of streamwise velocities along the same vertical profile used for high momentum injection at 30°. The range of streamwise velocities is much smaller than those observed for high momentum injection at 30°. Note that low momentum injection at 45° results in a similar range of streamwise velocities as low momentum injection at 30°. For the 45° and 30° slots at low momentum injection the endwall flow is not subject to intermittent vortices formed along the shear layer as in the high momentum flow case allowing the magnitude of the streamwise velocities to remain relatively stable.

5. Conclusions

Experiments were conducted to investigate the effects of flow injection angle on the stagnation plane flowfield and associated endwall heat transfer upstream of a rounded leading-edge and flat wall junction. A range of injection angles for a two-dimensional slot were considered for both high and low momentum injection.

Injecting high momentum flow upstream of the junction provided an increase in local turbulence levels and endwall heat transfer for each injection angle relative to the no injection slot case. A time-averaged vortex turning toward the endwall was formed in the stagnation plane for both 90° and 65° injection that was considerably larger than the vortex formed for the no injection slot case. While injection at 90° produced a vortex that remained stable, the vortex formed from injection at 65° was frequently disrupted by the boundary layer flow. The unsteadiness of the vortex for 65° injection produced higher turbulence levels and subsequently higher endwall heat transfer than 90° injection. For high momentum injection at 45° and 30° no time-averaged vortex on the endwall was measured. The injecting flow for the 45° and 30° slots resulted in strong shear layers along the endwall and an upwash of fluid at the corner of the junction. The production of counter-clockwise rotating vortices along the shear layer frequently disrupted the endwall flow leading to high turbulence levels and subsequently high endwall heat transfer relative to the no injection case. Downwash at the junction and the subsequent impingement of the boundary layer flow on the endwall provided increased heat transfer near the stagnation for injection at 90° and 65° in comparison to injection at 45° and 30° as no downwash was present. In contrast, heat transfer levels were higher near the exit of the injection slot for 45° and 30° in comparison to injection at 90° and 65°.

Reducing the injection momentum flux reduced the velocity difference between the injectant and near wall flow, substantially reducing the mixing and the resulting turbulence levels. In fact, low momentum injection for each slot angle resulted in turbulence levels in the same range as those observed with no injection slot, as a result the endwall heat transfer was similar. Although smaller in size and weaker in intensity than that observed for high momentum injection, a relatively steady vortex was formed in the stagnation plane for injection at both 90° and 65° with low momentum. Low momentum injection at 45° and 30° was mostly unable to counteract the strong turning of flow toward the endwall leading to the frequent formation of a vortex at the corner of the junction. The corner vortex, however, was consistently forced toward the leading-edge stagnation where the structure was eliminated.

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