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Swirl Boundary Layer at the Inlet of a Rotating Circular Cone

Ferdinand-J. Cloos¹, Peter F. Pelz¹*

Abstract
When a fluid enters a rotating pipe, a swirl boundary layer with thickness of \( \delta_S \) appears at the wall and interacts with the axial momentum boundary layer with thickness of \( \delta \). The swirl is produced by the wall shear stress and not due to kinematic reasons as by a turbomachine. In the center of the pipe, the fluid is swirl-free and is accelerated due to axial boundary layer growth. Below a critical flow number \( \varphi < \varphi_c \), there is flow separation, known in the turbomachinery context as part load recirculation.

Previous work analyses the flow at the inlet of a rotating circular pipe \( (\tilde{R} = 0) \). For a systematic approach to a turbomachine, the influence of the turbine’s and pump’s function, schematically fulfilled by a diffuser and a nozzle, on the evolution of the swirl and flow separation is to analyse. The radius of the rotating pipe depends linearly on the axial coordinate, yielding a rotating circular cone. The swirl evolution depends on the Reynolds number, flow number, axial coordinate and apex angle. The influence of the latter is the paper’s main task. The circumferential velocity component is measured applying 1D Laser Doppler Anemometry to investigate the swirl evolution.

Keywords
Swirl — Boundary Layer — Rotating Circular Cone — Pipe Flow
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INTRODUCTION
Turbomachines often operate at part load due to the claim of flexibility and not at the design point where the efficiency reaches its maximum. At part load for small flow numbers \( \varphi := \tilde{U}/(\tilde{R}_0\tilde{\Omega}) < \varphi_c \), with averaged axial velocity \( \tilde{U} \) (the superscript “~” indicates dimensional symbols whereas quantities without this superscript are dimensionless), circumferential velocity of the pipe \( \tilde{R}_0\tilde{\Omega} \), pipe radius at the inlet \( \tilde{R}_0 = \tilde{R}(\tilde{z} = 0) \) and axial coordinate \( \tilde{z} \), losses causing flow phenomena such as cavitation, rotating stall, part load recirculation and so on appear. These flow phenomena reduce the efficiency of a turbomachine compared to the efficiency at the design point.

The paper analyses the swirl development and distribution at the inlet of a rotating circular cone. The outcome of this work is useful to analyse and to predict swirl evolution, part load recirculation, flows in rotating gaps, e.g. secondary air flow of a gas turbine, and to clarify the inlet condition of turbo machines, e.g. shrouded turbomachines with a three dimensional boundary layer. Thus, this investigation supports the designers of the mentioned parts of a turbomachine.

Throughout this investigation, the paper nondimensionalises all velocities with the local cone circumferential velocity \( \tilde{\Omega}\tilde{R}(\tilde{z}) \) and lengths with the cone radius at the inlet \( \tilde{R}_0 \). In addition to that, all radial lengths are scaled on the local cone radius \( \tilde{R}(\tilde{z}) \).

To gain more physical knowledge about swirl evolution and part load recirculation, the paper uses a generic flow situation: a flow through a rotating circular cone. By this generic model, secondary flows, e.g. tip vortices as common by blades, are avoided, yielding a clear flow situation. Previous work analyses the flow at the inlet of a rotating pipe with a constant radius \( \tilde{R} = \tilde{R}_0 \) [1–6]. For a systematic approach to a turbomachine, the influence of a pump’s and turbine’s function on the evolution of the swirl and on the flow separation is to analyse. The pump’s function is to increase the pressure and this is schematically fulfilled by a diffuser. The turbine’s function is to decrease the pressure, obtaining a nozzle. Thus, the radius of the rotating circular cone depends linearly on the axial coordinate \( \tilde{R}(\tilde{z}) = \tilde{R}_0 + \tilde{z}\tan \alpha \) to accelerate or decelerate the flow with the apex angle \( \alpha \). Figure 1 illustrates the flow situation at the inlet of a rotating circular cone.

When an axial flow streams into the circular cone, an axial boundary layer with a thickness of \( \delta \) and an axial velocity profile \( u(y, \tilde{z}) \) with the wall coordinate \( y \) appears and develops close to the wall due to viscosity; see Fig. 1. Out-

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**Figure 1.** Flow through the inlet of a rotating circular cone.
side the axial boundary layer, the flow is irrotational and is accelerated due to boundary layer displacement. There, the axial velocity \( \dot{U}(z) \) and the static pressure \( P(z) \) are only a function of the axial coordinate. By rotating the circular cone, a second boundary layer in circumferential direction is produced by viscosity due to non-slip condition at the wall and develops. It is the so called swirl boundary layer with thickness \( \delta_s \) \([1–6]\). Inside the swirl boundary layer is a circumferential velocity component \( u_{\phi}(y, z) \), outside, the flow is swirl-free. There is a non-negligible radial pressure distribution \( p(y, z) \) inside the swirl boundary layer for \( \varphi \approx 1 \) due to the centrifugal force \([1, 4]\).

The evolution of the boundary layers depend on the Reynolds number \( Re := 2R_c\Omega/\nu \) with the kinematic viscosity \( \nu \), the flow number \( \varphi \) and the relative, averaged surface roughness \( R_c := \dot{R}_c/R_0 \). The paper’s main task is to quantify the influence of the apex angle on the swirl velocity profile and its turbulence intensity as well as on the swirl boundary layer thickness. Therefore, \( 1 \)D Laser Doppler Anemometry (LDA) is applied to measure the circumferential velocity profile. By doing so, two different inlet conditions are used: a thin laminar (configuration I) and a fully developed turbulent (configuration II) axial boundary layer at the inlet of the rotating circular cone.

This paper is structured as follows: First, it gives a literature review concerning the influence of swirl on velocity profiles and separation in the following section. \( \S 2 \) describes the experimental set-up. The gained results with this set-up presents \( \S 3 \). Finally, the main outcomes of this work are recapped in the closing of this paper.

1. LITERATURE REVIEW

The flow in a rotating pipe has been much more investigated at the fully developed region than at the inlet region. At the fully developed region, the boundary layers reach the pipe centre and the velocity profiles are independent of the axial coordinate. The boundary layers reach the centre for \( z > 10^2 \) for a turbulent flow, depending on Reynolds number and flow number \([7]\).

An interaction of the swirl and the axial momentum is observed by a complex transformation of the axial velocity profile at the inlet of a rotating pipe. Due to turbulence damping, the axial velocity profile transforms continuously from a turbulent into a laminar profile in axial direction when a fully developed, turbulent flow enters the rotating pipe \([8]\). This effect is called “laminarization” and has been observed in many investigations \([7, 9, 10]\). The “laminarized” profile reaches the fully developed region for a small flow number. For a higher flow number, the axial velocity profile is retransformed into the turbulent one \([7]\). An analytical approach of this transformation by Weigand and Beer \([11]\) meets the experimental results qualitatively, but the influence of the swirl is overestimated.

The swirl boundary layer with its velocity profile defines the evolution of the swirl. The circumferential velocity profile is parabolic \( u_{\phi} = r^2 \), when a turbulent flow enters the rotating pipe \([10, 12–14]\) and for a laminar flow it follows solid body rotation \( u_{\phi} = r \) \([10]\) at the fully developed region. Oberlack \([15]\) derived the profiles by Lie group analysis. In the transition region, the circumferential velocity profile is between the parabolic and the linear profile \([10]\).

When a thin laminar boundary layer enters a rotating pipe for \( \varphi > 0.71 \), the circumferential velocity profile transforms and both boundary layers are thickened at the inlet of a rotating pipe \([7]\). At the inlet for a smaller flow number \( \varphi \leq 1 \) with a fully developed turbulent or a thin laminar or turbulent axial boundary layer, the circumferential velocity profile follows

\[
u_{\phi} = \left(1 - \frac{y}{\delta_s}\right)^2, \quad (1)
\]

for regime I and an attached flow \([1–5]\). For the fully developed axial turbulent flow, the measured swirl boundary layer thickness follows

\[
\delta_{S02} = C R e^{m_R e} \varphi^{m_\varphi} z^{m_z}, \quad (2)
\]

with \( \delta_{S02} := \gamma(\nu_{\phi} = 0.02), C \approx 4.43, m_{Re} \approx -0.45, m_\varphi \approx -0.46 \) and \( m_z \approx 0.47 \). For a thin axial boundary layer, the constant \( C \) is approximately \( 4.64 \) with \( m_{Re} \approx -0.46, m_\varphi \approx -0.49 \) and \( m_z \approx 0.44 \) \([4, 5]\). The swirl boundary layer becomes independent of the Reynolds number for a hydraulically rough flow but still depends on the flow number \([1, 4]\).

For a hydraulically rough flow, the circumferential velocity profile follows more or less \( u_{\phi} = (1 - y/\delta_s)^2 \gamma \) \([4]\).

Equation \( 2 \) for a thin axial boundary layer is confirmed by our analytical approach \([1, 4]\). By this approach, we use the integral method of boundary layer theory and generalize the von Kármán momentum equation taking the influence of swirl by a radial pressure distribution into account. A strong influence of the swirl, i.e. the centrifugal force, on the axial momentum balance is observable for small flow numbers \( \varphi \ll 1 \). The centrifugal force causes flow separation for a small flow number and a measured stability map for part load recirculation is given \([1, 4–6]\). When the flow separates, the circumferential velocity profile differs from the parabolic one \([1, 4, 5]\). Stratford’s criteria \([16]\) is applied to derive the critical flow number for incipient separation analytically and the results are validated by experiments \([1]\). For small Reynolds number, i.e. laminar flow, flow separation is investigated by Lavan and others in a rotating pipe \([17–19]\).

For high Reynolds number as well as high flow number Eqn. \( 2 \) is no longer valid because a second transition of the swirl boundary layer occurs in the turbulent regime \([2–4]\). At this transition \( (Re, \varphi, z) > (Re, \varphi, z_t) \) (the subscript \( t \) indicates the point of transition from regime I to II), the circumferential velocity profile transforms from the parabolic profile Eqn. \( 1 \) of regime I into

\[
u_{\phi} = \frac{k}{2} \log \left(1 - \frac{y}{\delta_s} + A \right) + B \quad (3)
\]

of regime II with the constants \( A = 0.007, B = 0.06 \) and \( k = 0.4 \) \([2, 3]\). Furthermore, the swirl boundary layer thickens...
2. EXPERIMENTAL SET-UP

A test-rig is designed to measure the evolution of the swirl boundary layer and the circumferential velocity component in a rotating cone applying 1D LDA and is used by previous investigations [1–6].

The air flow at ambient pressure is provided by a side channel blower, which increases pressure in a large plenum chamber, not shown in Fig. 2. In this plenum chamber, the air temperature is measured. The outlet of the plenum chamber is followed by a first flow straightener; cf. Fig. 2. Hence, pulsations are minimized. The volume flow is measured by an orifice plate and the flow is varied by changing the rotation speed of the blower. Thus, the axial velocity is controlled. The maximum axial velocity is 30 m/s, resulting in a Mach number smaller than 0.1.

Downstream of the flow measurement, an exchangeable section for different inlet conditions is implemented; see Fig 2. Both configurations include a second flow straightener. By configuration I, three turbulence screens are installed between a diffuser and the Börger-Nozzle [24]. By means of this nozzle, a thin axial boundary layer is generated due to flow acceleration, thus a bulk like velocity profile. Downstream of the Börger-Nozzle, the flow enters the rotating cone as illustrated in Fig. 2. At the inlet of the rotating cone, the axial boundary layer has a thickness of \( \delta = 8 \ldots 12 \% \) with a laminar profile and \( Tu_1 := \bar{u}_1/\bar{u}_\infty = 1 \ldots 2 \% \) outside the boundary layer for \( \bar{U} \leq 8 \text{ m/s} \). Inside the boundary layer, the turbulence intensity increases approximately to 6 %. For configuration II, an obstacle is installed, see Fig. 2b, to generate a fully developed, turbulent axial boundary layer. At the inlet of the rotating cone, the axial boundary layer thickness is 1 for \( \bar{U} \geq 2 \text{ m/s} \). The turbulence intensity is approximately 4 % and 13 % in the pipe centre and closer to the wall, respectively. The inlet conditions of both configurations are measured by a hot wire anemometer.

Between the non-rotating and rotating part is an axial gap of 4% \( R_0 \). The gap is sealed by sealed ball bearings. The rotating cone is exchangeable and seven inserts are used. Three circular cones have a negative apex angle \( \alpha = -1.83 \, ^\circ, -1.08 \, ^\circ, -0.61 \, ^\circ \), another three with a positive apex angle \( \alpha = 0.47 \, ^\circ, 1.03 \, ^\circ, 1.55 \, ^\circ \) and one circular pipe with \( \alpha = 0 \, ^\circ \). The apex angles are chosen in such a range that flow separation is avoided when the circular cone does not rotate. The inlet radius and the total length of the rotating cones is always \( R_0 = 25 \text{ mm} \) and \( 5R_0 \), respectively. The surface has a relative, averaged surface roughness of 0.04% \( R_0 \) for the blank cones. The roughness is determined applying the focus variation method. The rotating cone is driven by a belt with a maximum rotational speed of \( \Omega = 1308 \, \text{ rad/s} \), yielding a maximum Reynolds number of \( \log(Re) = 5.1 \). Hence, Reynolds number and flow number are independent of each other. The outlet of the cone is a free jet. The advantage of this design is a convenient accessibility from downstream to the flow field within the rotating cone; see Fig. 3.

![Figure 2. Experimental set-up with a) configuration I for a thin axial boundary layer and b) configuration II for a fully developed axial boundary layer.](image)

![Figure 3. Laser beam path into the rotating pipe of the 1D Laser Doppler Anemometry.](image)
light through any solid material and are not deflected. An aerosol of silicon oil as tracer particles is added to the air to enable LDA measurements; see Fig. 2. The LDA and the experimental set-up is described in more detail by [1, 4, 5].

The positioning of the LDA measuring volume has a systematic measuring error of \( \Delta z_{\text{sys}} \approx \pm 8 \% R_0 \) and \( \Delta \tilde{y}_{\text{sys}} \approx \pm 4 \% R_0 \). The repetitive accuracy in both directions of the traverse table is \( 0.8 \% R_0 \). One LDA data point is measured over more than 30 s including more than 1000 bursts. The transit time of each passing tracer particle is used to weight the measured velocity.

The maximum systematic measuring error of Reynolds number is less than \( \Delta R e_{\text{sys}}/R e \leq \pm 4 \% \) and of the flow number it is less than \( \Delta \varphi_{\text{sys}}/\varphi \leq \pm 5.5 \% \) for \( \varphi = 0.35 \) and \( \log(Re) = 4.1 \). The systematic measuring errors of the Reynolds number and the flow number decrease with increasing Reynolds number and flow number, respectively. Both quantities include 200 data points, obtaining a negligible precision error compared to the systematic error since the standard deviation is small. Nevertheless, both measuring errors are taken into account for the total measuring error. In the following, all presented data points consider the total measuring error visualized by error bars. Usually, the error bars are smaller than the marker, thus they are not visible. The precision error of \( \tilde{u}_{\phi, \text{rms}} \) is unknown.

3. RESULTS

This section presents the measured swirl boundary layer thickness, the swirl velocity profile and its turbulence intensity. Hereby, both configurations are used and their influence as well as of the apex angle are discussed.

3.1 Swirl Boundary Layer Thickness

![Figure 4](image)

**Figure 4.** Interpolated isolines of \( u_\phi \) shows the development of the swirl boundary layer for configuration I. Measurement points are illustrated by the markers.

The development of the swirl boundary layer is well depicted by the isolines of \( u_\phi \) in figure 4. Between the measurement points, illustrated by the markers, the swirl velocity is interpolated. By doing so, the swirl boundary layer thickness \( \delta_{S02} \) and \( \delta_{S07} := y(u_\phi = 0.07) \) are obtained. For configuration II, the outer region of the swirl boundary layer is the duty of higher fluctuations due to the higher turbulence intensity than for configuration I; cf. § 2. This is the reason for analysing the isoline \( \delta_{S07} \) for configuration II instead of \( \delta_{S02} \) as it is done for configuration I.

Figure 5 and 6 show the measured swirl boundary layer thickness for different apex angles and various cross-sections, Reynolds number and flow number for configuration I and II, respectively. Analysing the swirl boundary layer thicknesses in both figures, the swirl boundary layer thicken for increasing apex angle, especially for \( z \gtrsim 1 \). For a positive apex angle, the boundary layer is noticeable thicker than for a negative or a vanishing apex angle.

Analysing the slope of the boundary layer thickness in the double-logarithmic diagrams (Fig. 5 and 6) for each parameter far away from the singularity at \( z = 0 \), the thickness \( \delta_{S02} \) and \( \delta_{S07} \) follow the power law Eqn. 2. A calibration of the power law is necessary to obtain the constant \( C \). The constants \( C, m_{Re}, m_\varphi \) and \( m_z \) depend on the configuration, more or less on the apex angle but are independent of the other parameters; cf. Tab. 1 and 2. The total error is \( \Delta m_{\varphi} \approx \pm 0.03 \) and of \( \Delta C \approx \pm 0.1 \). Constant \( m_{\varphi} \) and \( C \) change most by varying the apex angle and increase by increasing apex angle; see Fig. 5c and 6c. Constant \( m_z \) depends on the sign of the apex angle. Hence, the apex angle has a noticeable influence on the evolution of the swirl boundary layer thickness.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( C )</th>
<th>( m_{Re} )</th>
<th>( m_\varphi )</th>
<th>( m_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-1.83^\circ)</td>
<td>4.19</td>
<td>-0.46</td>
<td>-0.54</td>
<td>0.44</td>
</tr>
<tr>
<td>(-1.08^\circ)</td>
<td>4.25</td>
<td>-0.45</td>
<td>-0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>(-0.61^\circ)</td>
<td>4.55</td>
<td>-0.46</td>
<td>-0.45</td>
<td>0.44</td>
</tr>
<tr>
<td>(\pm 0.00^\circ)</td>
<td>4.64</td>
<td>-0.46</td>
<td>-0.49</td>
<td>0.44</td>
</tr>
<tr>
<td>(+0.47^\circ)</td>
<td>6.45</td>
<td>-0.47</td>
<td>-0.35</td>
<td>0.37</td>
</tr>
<tr>
<td>(+1.03^\circ)</td>
<td>6.63</td>
<td>-0.50</td>
<td>-0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>(+1.55^\circ)</td>
<td>10.3</td>
<td>-0.47</td>
<td>-0.22</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 1. Constants for the power law Eqn. 2 for \( \delta_{S02} \) and configuration I.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( C )</th>
<th>( m_{Re} )</th>
<th>( m_\varphi )</th>
<th>( m_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-1.83^\circ)</td>
<td>2.47</td>
<td>-0.41</td>
<td>-0.46</td>
<td>0.44</td>
</tr>
<tr>
<td>(-1.08^\circ)</td>
<td>3.51</td>
<td>-0.45</td>
<td>-0.47</td>
<td>0.44</td>
</tr>
<tr>
<td>(-0.61^\circ)</td>
<td>4.78</td>
<td>-0.48</td>
<td>-0.44</td>
<td>0.45</td>
</tr>
<tr>
<td>(\pm 0.00^\circ)</td>
<td>3.16</td>
<td>-0.43</td>
<td>-0.40</td>
<td>0.41</td>
</tr>
<tr>
<td>(+0.47^\circ)</td>
<td>3.99</td>
<td>-0.44</td>
<td>-0.38</td>
<td>0.35</td>
</tr>
<tr>
<td>(+1.03^\circ)</td>
<td>5.07</td>
<td>-0.46</td>
<td>-0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>(+1.55^\circ)</td>
<td>5.86</td>
<td>-0.47</td>
<td>-0.28</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 2. Constants for the power law Eqn. 2 for \( \delta_{S07} \) and configuration II.
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Figure 5. Swirl boundary layer thickness $\delta_S02$ with various apex angle versus a) axial coordinate, b) Reynolds number and c) flow number for configuration I.

Figure 6. Swirl boundary layer thickness $\delta_S07$ with various apex angle versus a) axial coordinate, b) Reynolds number and c) flow number for configuration II.

The deviation of the power law with the given exponents from the experimental data is less than 5%. The constants and the power law are only valid for regime I of the swirl boundary layer, hydraulically smooth flow (cf. §1) and for $z < 4$. At $z = 4$, the influence of the outlet is visible and the swirl boundary layer becomes suddenly thinner. This influence is already known by previous investigations [1,4,5]. The data points of the transition and regime II of the swirl boundary layer are not shown by Fig. 5 and 6 for a better readability.
Figure 7. Swirl velocity profile for various axial coordinate, Reynolds number, flow number and apex angle for a)-d) configuration I, a thin axial laminar boundary layer, and for e)-h) configuration II, a fully developed axial turbulent boundary layer.

3.2 Swirl Velocity Profile

Figure 7 shows the swirl velocity profile versus the scaled wall coordinate for various axial cross section, Reynolds number, flow number, apex angle and both configurations. For configuration I (Fig. 7a-d), the wall coordinate $y$ is scaled on the swirl boundary layer thickness $\delta_{S02}$ and for configuration II (Fig. 7e-h), it is scaled on $\delta_{S07}$.

The swirl velocity profile is self-similar and follows well the distribution given by Eqn. 1 at the inlet of a rotating circular cone for regime I of the swirl boundary layer. It is
indeed necessary to nondimensionalise the swirl velocity with the local wall velocity otherwise the swirl velocity profile would not be self-similar neither fit Eqn. 1. The measured profiles are independent of the inlet condition, configuration I and II, and of the varied values \( z, Re, \varphi, \alpha \) as Fig. 7 illustrates. For \( z \leq 0.250 \) there are some recognizable deviations from the parabolic profile. Fig. 7 illustrates the transformation of the swirl velocity profile from regime I to regime II of the swirl boundary layer; cf. [2–4]. Thus, regime II is occurs as well for \( \alpha \neq 0 \).

3.3 Turbulence Intensity

Figure 8 depicts the turbulence intensity of the swirl velocity for the same parameter combinations as the swirl velocity distribution is presented by Fig. 7. As it is known by the previous investigations for \( \alpha = 0 \) [2–4], the turbulence intensity is higher for configuration II than I. This is due to the higher turbulence intensity of the axial velocity at the inlet of the rotating cone; cf. §1.

For configuration I and regime I, the turbulence intensity \( Tu_0 \) is self-similar for the outer region \( y/\delta_S02 \gtrsim 0.7 \). At the inner region \( y/\delta_S02 \lesssim 0.7 \), the turbulence intensity depends on the axial coordinate, Reynolds number and flow number but not on the apex angle; see Fig. 8a–d. There, the turbulence intensity decreases with increasing axial coordinate and decreasing Reynolds number and flow number, respectively. For \( z \gtrsim 1 \), the turbulence intensity is self-similar for the inner and outer region.

For configuration II and regime I, the turbulence intensity is more or less self-similar and independent of the axial coordinate, Reynolds number and apex angle. For increasing flow number, the turbulence intensity increases at the inner and outer region; see Fig. 8g. For increasing Reynolds number, the turbulence intensity increases slightly at the inner region. For high Reynolds number, the transition to the turbulent regime II of the swirl boundary layer indicated by the swirl profile transformation (Fig. 7f) occurs. Hereby, the turbulence intensity increases strongly and yields the known self-similarity of regime II [2, 3].

4. CONCLUSION

This paper investigated the influence of the apex angle \( \alpha \) on the evolution of the swirl at the inlet of a rotating circular cone. By doing so, three negative (nozzle), three positive (diffuser) and one vanishing apex angle (pipe) were applied. Furthermore, the influence of the inlet condition was investigated with two flow configurations. The measured evolution of the swirl by LDA is well described by a power law Eqn. 2 for the swirl boundary layer thickness taking the axial coordinate, Reynolds number and flow number into account. The constants for this power law depend more or less on the apex angle; see Tab. 1 and 2. The swirl boundary layer is thicker for positive than for negative apex angles for \( z \gtrsim 1 \).

Within the swirl boundary layer, the circumferential velocity distribution follows the well-known parabolic profile Eqn. 1 for regime I of the swirl boundary layer; see Fig. 7. The transition to regime II of the swirl boundary layer occurs as well for \( \alpha \neq 0 \).

The turbulence intensity is self-similar for the outer region. At the inner region, the turbulence intensity depends on the axial coordinate for \( z \lesssim 1 \), Reynolds number and flow number but is independent of the apex angle; see Fig. 8.

Finally, this investigation improves the physical knowledge and understanding of swirl evolution. The gained knowledge is employable for the design of a turbomachine, especially a shrouded turbomachine and rotating flow channels of secondary air flow of a gasturbine.

REFERENCES

Figure 8. Turbulence intensity of the swirl velocity for various axial coordinate, Reynolds number, flow number and apex angle for a)-d) configuration I, a thin axial laminar boundary layer, and for e)-h) configuration II, a fully developed axial turbulent boundary layer.


