EVOLUTION OF SWIRL BOUNDARY LAYER AND WALL STALL AT PART LOAD
– A GENERIC EXPERIMENT

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ABSTRACT
The influence of Reynolds number, roughness and turbulence on the onset of wall stall is up to now not sufficiently understood. To shed some light onto the interdependency of near wall flow with growing swirl component, the simplest “machine” is tested. The apparatus we examine is a circular pipe at rest followed by a rotating co-axial pipe segment. In the sense of a generic experiment this machine represents a very basic model of the inlet of an axial machine. Due to the wall shear stress a swirl boundary layer is formed in the rotating pipe segment, interacting with the axial boundary layer. The evolution of the swirl velocity profile with increasing axial distance from the rotating pipe inlet is measured for various Reynolds numbers, flow numbers and degrees of turbulence by means of Laser Doppler Anemometry. We observe a self-similarity in the swirl velocity profile, for subcritical flow number and develop a scaling law for the velocity distribution in the transition section of a rotating pipe. At critical flow number the boundary layer is separating, resulting in a ring vortex at the inlet of the rotating pipe. Our work fills the gap of previous experimental works, with respect to high Reynolds numbers and low flow numbers. The parameter field we examine is most relevant for turbomachinery application and wall stall. In addition our boundary layer resolution is sufficient to resolve the swirl boundary layer thickness. Only this high resolution enables us to generalize the experimental findings by means of a similarity distribution of the velocity profile within the swirl boundary layer.

NOMENCLATURE
- $C$: factor
- $L$: length of the rotating pipe
- $R$: radius of the rotating pipe
- $Re$: Reynolds number
- $Tu$: degree of turbulence
- $\bar{U}$: mean velocity
- $U_e$: free stream velocity
- $\bar{u}$: time averaged fluctuation
- $k$: exponent for swirl velocity distribution in transition section
- $n$: exponent for critical flow number
- $r, z, \varphi$: coordinate
- $s$: gap width
- $u_e, u_z$: velocity component
- $y$: wall coordinate
- $y_f$: wall coordinate of measurement volume

Greek Symbols
- $\beta$: exponent for axial and swirl velocity distribution in saturated section
- $\eta$: generalized wall coordinate
- $\kappa$: roughness
- $\nu$: kinematic viscosity
- $\delta$: boundary layer thickness
- $\Omega$: angular frequency
- $\varphi$: flow number (dimensionless mean velocity)
- $\Theta$: momentum loss thickness

Subscripts
- $c$: critical
- $S$: swirl
- $S02$: 2% swirl velocity isoline

1 INTRODUCTION
Turbomachines often operate below optimal capacity (at small flow number $\varphi$) in order to fulfill varying application requirements. When the flow number drops below a critical limit, the boundary layer separates and forms a part load recirculation (wall stall). This process limits the characteristic diagram for economic and reliable operation. Responsible for the separation is the positive pressure gradient caused by the
growing swirl in the impeller. Due to the interdependency of several secondary flows in the impeller, the physical interaction of the swirl on the boundary layer is not sufficiently understood for a dependable prediction of the onset of the part load recirculation. A deeper understanding of swirl driven separation will enhance the predictability of part load recirculation and support the development of methods for active flow control in turbomachinery. Hence, for studying the fundamental physics of swirling flow we investigate the evolution of swirl and the onset of part load recirculation in the most abstract form of a turbomachine: the transition from a pipe at rest to a rotating coaxial pipe, shown in Fig. 1. For reducing the complexity we use an “impeller” without blades. This generic configuration simulates the impeller inlet and enables an investigation of wall stall and the influences of several parameters on its onset without interdependency of secondary flows like i.e. incidence and blade stall. In this paper we present the experimental study of the generic configuration concerning:

(i) development of the swirl boundary layer,
(ii) self-similarity in the swirl velocity distribution and
(iii) boundary layer separation caused by swirl.

First of all we make a dimensional analysis to describe the characteristical parameters of the swirling flow. Physical quantities with a dimension are marked by tilde “̃”, whereas the tilde is omitted for dimensionless quantities.

![Fig. 1: Generic model and the evolution of swirl boundary layer.](image)

We differentiate the axial boundary layer thickness ̃δ and the swirl boundary layer thickness ̃δs. The swirl boundary layer is defined as that wall distance ̃y up to which the flow has a swirl component ̃uφ(̃y, ̃z), the flow outside the swirl boundary layer is swirl free.

The pipe radius ̃R is chosen as characteristic length and the rotational velocity of the pipe ̃ΩR is chosen as characteristic speed. The dimensional analysis shows the dependency ̃δs/̃R = ̃δs(φ, Re, uφ, z, s, k, Tu), with the dimensionless Reynolds number Re = 4̃Ω̃R2/ν, average flow velocity (flow number) ̃U := φ = ̃U/(̃Ω̃R), swirl velocity distribution uφ = ̃uφ/(̃Ω̃R), axial distance to the entry z = ̃z/̃R, relative roughness κ = ̃κ/̃R, gap width s = ̃s/̃R, and the degree of Turbulence Tu := u′u′/̃U. The boundary layer separates from the rotating wall and recirculates below a critical average flow ̃Uc respectively below a critical flow number ̃φc := ̃Uc/(̃Ω̃R).

![Fig. 2: Science landscape for the flow in a rotating pipe with the scope on flow distribution and flow reversal.](image)

2 REVIEW ON PREVIOUS WORK

The development of swirl and its influence on axial flow and turbulence is part of different previous investigations. For classifying them, it is useful to divide the generic experiment into 3 sections. (i) The non-swirling inlet far upstream of the transition to the rotating pipe as a singularity in boundary condition. (ii) The transition section where the swirl boundary layer develops and (iii) the saturated section far downstream of the singularity, where the swirl boundary layer has fully developed. Fig. 2 shows the parameter field of flow number and Reynolds number of previous studies according to the investigated section. It shows that the transition section for small flow and high Reynolds numbers is up to now only crudely investigated.

The flow separation in the generic model for laminar flow with small Reynolds number is analytically, experimentally and numerically well investigated. For the laminar case, the critical flow number increases with increasing Reynolds number ̃φc ~ Re [1], [2], [3], [4], [5]. In the pre-studies of this work [6] it was shown by experimental and numerical studies that for turbulent flow the critical flow number decreases again with ̃φc ~ Re−n.

Several experimental, numerical and also analytical studies investigated the attached turbulent flow in the fully developed section. The scope of the most renowned studies can be divided into the objectives axial velocity profile [7], [8], [9], [10] turbulence [11], [12], [13], [14], [15], [16], [17] and swirl velocity distribution [7], [18].

For the saturated flow it is known [12], that the influence of swirl causes a so called laminarization effect on the turbulent axial velocity distribution. Therefore, even at high Reynolds number a parabolic profile in the saturated region exists. Semi analytical relations are known [19] which describe the influence of swirl on the axial velocity distribution based on an advanced logarithmic law and an advanced mixing length model. Thus, the axial velocity profile is scaled by the parameter Z = 1/φ√̄λ/β where λ is the friction coefficient.

In the saturated section, the swirl velocity profile is sufficiently described by measurements [11], [13], [18]. Hence, it is known that in this section the swirl velocity distribution for turbulent flow is parabolic, independent of the flow number. This result is in good accordance with Lee-group analysis.
which predicts the distribution to follow the power law \( u_\varphi = r^\beta \), with an exponent \( \beta = 2 \) for fully turbulent flow and \( \beta = 1 \) for laminar flow [7]. The Lee-group analysis also confirms the swirl caused changeover of the axial velocity distribution from the turbulent to a parabolic distribution. Furthermore, this analysis predicts that the axial velocity distribution will also follow a power law in the saturated section and will have the same exponent \( \beta \) as the swirl velocity distribution.

The development of flow in the transition section is less investigated than in the saturated section. Experimental researches for the development of the turbulent flow are presented in [12], [18] and [20].

For the transition section an empiric function for the swirl velocity distribution is known that approximates the influence of the distance to the entry by a variable function in the exponent with \( u_\varphi = r^{2+f(z)} \) and \( f(z) = 1/z + 9.5e^{-0.0192z} \) [20]. But this function does not represent the influence of flow number and Reynolds number on the swirl boundary layer thickness and therefore on the velocity distribution. It approximates the velocity distribution only acceptably for large distances to the entry where the flow is nearly saturated.

We also find a definition of a momentum thickness in circumferential direction with \( \Theta_{xy} = \int_0^\delta u_x/U_e \ u_\varphi r^2 dy \) and measurements at the transition section in literature. Thereby, for large flow number \( (\varphi > 1) \) an approximation of the swirl velocity scaled with the axial momentum thickness

\[
 u_\varphi = 1 - \left( \frac{1}{\Theta_x} \right)^{0.3}
\]

with \( \Theta_x = \int_0^\delta u_x/U_e(1-u_x/U_e)r dy \) is given [18]. This approximation does not represent the evolution of the swirl velocity with growing distances to the entry. Both quantities for the momentum loss thickness \( \Theta_x, \Theta_{xy} \) decrease with decreasing flow number but the swirl velocity distribution remains independent from the number in the investigated interval \( 4 > \varphi > 1 \). As cause for the suppression of the boundary layer, pipe rotation is indicated [18]. The rotation influences the turbulence strongly. At the section immediately downstream of the inlet \( (z < 20) \), the Reynolds stresses are increased due to the shear stress caused by rotation. Far downstream of the inlet \( (z \geq 20) \), the turbulence intensity gradually decreases to below the value of the pipe at rest [18].

The present work focuses on the less investigated but - for turbomachinery and concerning wall stall - most important transition section with small flow number \( (\varphi < 1) \) and large Reynolds number. In addition to previous work, we experimentally observe the self-similarity of the swirl velocity distribution and therefore the evolution of a swirl boundary layer for the first time.

### 3 EXPERIMENTAL SETUP

For the experimental investigation a free stream channel with a radius of \( \bar{R} = 25 \text{ mm} \) and air at room temperature is used. The Mach number of the flow is smaller than 0.1 and the flow is in the time average stationary.

The air flow for the experiment is provided by a radial fan. To reduce pulsating, the fan is separated from the channel by a large plenum chamber and a flow resistance. At the inlet to the channel, an aerosol of silicon oil as tracer particle is added to the air to enable the Laser Doppler Anemometry (LDA) measurement. The volume flow is measured by an orifice plate flow measurement. There are two different experimental setup of pre flow conditioning for vary the turbulence.

First, in setup I, for low turbulence the air flows through a pipe of a length \( 80\bar{R} \) followed by a plenum chamber. This is connected to a diffusor and has the diameter of \( 4\bar{R} \). It includes a flow rectifier and three turbulence screens. After that, a Börger-nozzle [21] optimized for high flow uniformity, low turbulence and a bulk like velocity profile follows and leads the air into the rotation unit (Fig. 3).

![Fig. 3: Experimental setup I for low turbulence.](image)

Second, in setup II the large plenum chamber and Börger-nozzle is replaced by an integrated plenum chamber of a diameter \( 2\bar{R} \), behind that a pipe segment of \( 60\bar{R} \) length and an obstacle of \( 1 \text{ mm} \) height resulting in a much higher degree of turbulence (Fig. 4).

![Fig. 4: Experimental setup II for high turbulence.](image)

For technical reasons there is an axial gap between the stationary and rotating pipe segment showing an axial width of \( s = 0.4\% \). To avoid leakage through the gap, the spindle ball bearings are sealed. Its maximal angular velocity amounts to \( \hat{\omega}_{max} = 1251 \text{ sec}^{-1} \), respectively \( \lg(\hat{R}e_{max}) = 5.31 \). The length of the rotating pipe segment is chosen to be \( 5\bar{R} \) and a relative roughness of \( \kappa < 10^{-4} \). The previous numeric studies [6] showed no influence of the slenderness for \( \bar{L}/\bar{R} > 5 \) and of the roughness for \( \kappa < 10^{-4} \) on the critical flow number justifying this design decision.

To measure the flow field, a 1D LDA system with frequency shift is used. The added tracer particles are aerosol of silicon oil. Every LDA measurement point is averaged over \( \geq 30 \) seconds and consists of at least 500 single points. The probe for the 1D LDA measurement has a focus of \( 315 \text{ mm} \) and
is located downstream of the outlet in an angle of 12 degrees. Its positioning is shown in Fig. 5.

The probe is adjusted to measure only the swirl component of the flow and can be moved in a 2 dimensional plain with the use of a traverse table. The measurement volume has the length of < 0.4 mm and a diameter of < 0.05 mm. It is located at the wall distance \( y_f = y_0/R \) and the accuracy of positioning of the measurement volume is approximated as ±0.1 mm in the plain. With the described LDA system a measurement of the swirl velocity up to a wall distance of only 0.4 mm is possible. The mean variation of the measured swirl velocity is smaller than ±0.02 m/s.

The two different experimental setups of the pre flow channels differentiate in the degree of turbulence and in the axial profile of the provided flow steam. For quantifying the degree of turbulence a hot wire anemometer at the centerline of the pipe at \( z = 0 \) was used during a preliminary inspection. Fig. 6 shows the result of the turbulence measurement. In setup II the inlet flow for a mean velocity higher than 2.1 m/s can be considered as fully turbulent and for setup I in the whole range of tested flow velocity the degree of turbulence is smaller than 1% and nearly constant.

4 SWIRL BOUNDARY LAYER

We define a swirl boundary layer in analogy to the well-known momentum boundary layer. Hence we investigate the swirl extend into the flow field and examine how it is influenced by Reynolds and flow number.

When the flow enters the rotating pipe, due to the wall shear stress a swirl velocity component and therefore a swirl boundary layer develops and grows downstream. Analog to the axial boundary layer theory, we divide the measured flow field into two regions. Outside the swirl boundary, in the core region of the pipe the flow is free of angular momentum, with \( \omega_c \approx 0 \). Inside the near region, i.e. inside the swirl boundary layer, \( \omega_c > 0 \) resulting in a radial pressure profile. Fig. 7 shows an LDA measurement result in form of \( u_\varphi \) isolines. The red curve marks the isoline \( u_\varphi = 0.02 \), giving a good impression of the swirl boundary layer development downstream. We define this curve for \( \delta_{502} \), whereby \( \delta_s \sim \delta_{502} \). The markers show the measurement positions, they are located on constant length coordinate \( z \) with a radial step width less than 0.1 mm.

As long as the flow is attached there is no swirl velocity component for \( z < 0 \). Fig. 8 and Fig. 9 show the development of the swirl boundary layer thickness along the pipe length coordinate. Reynolds and flow number are varied independent. Obviously the swirl boundary layer thickness follows a power law \( \delta_{502} \sim C(Re, \varphi)z^{m_2} \), for \( z \leq 4 \). Since the pipe length is \( L = 5 \) thus it is assumed, that the finite length has an effect on the thickness at \( z = 4 \).
Fig. 10 shows the influence of Reynolds number and Fig. 11 the influence of flow number on the swirl boundary layer thickness. In both cases we observe power laws and end up with the power law of the form

$$\delta_{S02} = C_{S02}Re^{m_1} \varphi^{m_2} z^{m_3},$$

with the exponents $m_1 \approx -0.44 \pm 0.05$, $m_2 \approx -0.48 \pm 0.05$, $m_3 \approx 0.44 \pm 0.05$ and the factor $C_{S02} \approx 5.3 \pm 0.5$ for the experiments, which are done so far.

![Graph showing influence of Reynolds number on swirl boundary layer thickness](image)

**Fig. 10:** Influence of Reynolds number on the swirl boundary layer thickness with setup I.

The influence of the degree of turbulence on the swirl boundary layer thickness is shown for both pre conditioning setups on Fig. 12. As Fig. 6 shows for the experimental setup I, the degree of turbulence is due the Börger-nozzle, showing a value of $Tu \approx 0.01$, whereby for setup II the degree of turbulence is factor 2...10 higher depending on the mean flow velocity.

At high flow number, both setups yield to experimental results described by the very same power law. In the case of higher turbulence the swirl boundary layer is thicker compared to the low turbulence case, therefore $C_{S02}$ is a function of $Tu$. Below a critical flow number, the swirl boundary layer thickness increases sharply with decreasing flow number. The reason for this is the separation of the axial boundary layer and with that the onset of a recirculation vortex that carries swirling fluid upstream. The wall stall represents the lower limit in flow number for the validity of the power law for the swirl boundary layer thickness. The critical flow number is investigated and quantified for different Reynolds number in Section 6.

![Graph showing influence of flow number on swirl boundary layer thickness](image)

**Fig. 11:** Influence of flow number on the swirl boundary layer thickness with setup I.

![Graph showing influence of turbulence on swirl boundary layer thickness](image)

**Fig. 12:** Influence of turbulence on the swirl boundary layer thickness.

### 5 SIMILARITY OF SWIRL VELOCITY PROFILE

In this Section we show a self-similarity of the swirl velocity profile within the swirl boundary layer. Therefore we introduce the dimensionless wall coordinate $\eta := y/\delta_{S02}$ depending on the boundary layer thickness. In the comparison of $u_\varphi(y,z)$ and $u_\varphi(\eta)$ in Fig. 13, we see that this scaling leads to a self-similar velocity profile (i.e. master curve) and $u_\varphi(\eta)$ is independent of the axial distance to the entry. By using this self-similarity the swirl velocity field in the transition section is described only by the swirl boundary layer thickness, which is known from the previous Section of this work. The self-similarity of the swirl velocity distribution can be approximated by

$$u_\varphi = (1 - \eta)^k,$$

whereby the measurements under condition of the tested parameters and depending on the measurement accuracy are fitted best for the value of $k = 1.85 \pm 0.15$. The independency of the self-similarity from the axial distance is validated for $z \leq 4$ at several combinations of Reynolds and flow number (here not shown).

![Graph showing self-similarity of swirl velocity distribution](image)

**Fig. 13:** Self-similarity of swirl velocity distribution, influence of length, with setup I. The red filled markers are for $u_\varphi(y,z)$, the empty markers are for $u_\varphi(y,\eta)$. 

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As Fig. 14 and Fig. 15 show, there is only a minor influence of the flow number and the Reynolds number on the generalized velocity profile in the observed parameter interval.

Fig. 14: Self-similarity of swirl velocity distribution, influence of flow number with setup I.

Fig. 15: Self-similarity of swirl velocity distribution, influence of Reynolds number with and setup I.

To investigate the sensitivity of $u_\varphi(\eta)$ on the degree of turbulence and flow separation, the experimental setup II is used for the pre flow conditioning. The flow number is varied in an interval that leads from an subcritical, attached state with $\varphi > 0.225$ to an over critical, separated state with $\varphi < 0.225$. The measured velocity profiles are shown in Fig. 16. For attached flow we find again the self-similarity in the swirl velocity. The exponent $k$ has the value of $1.85 \pm 0.15$.

Fig. 16: Self-similarity of swirl velocity distribution vs. flow number, influence of turbulence and flow separation, with setup II.

For a flow number below the critical, the flow separation causes a deformation of the velocity profile, which can clearly be seen for small flow number $\varphi \leq 0.2$. Therefore the separation limits the legal interval of flow number for the self-similarity.

6 FLOW SEPARATION AT SMALL FLOW NUMBER

In the generic model, the flow separation and therefore the wall stall are of particular interest. This is because when the flow separates, we observe a strong deviation of the (swirl) velocity distribution from the generalized one. To identify the critical flow number, the swirl component in the static pipe is used as an indicator. In case of a flow separation a backflow transports the swirl velocity upstream and causes a pre swirl in front of the rotating pipe. Therefore, the measurement volume is positioned at the entry of the rotating pipe at $z = 0$. Fig. 17 shows the measured swirl velocity over varying flow number for different wall distances of the measurement volume. While the flow is attached, the swirl component at the inlet is very small and only affected by pre-rotation from the mixing zone in the gap. The swirl boundary layer during attached flow at $z = 0$ is very thin and does not reach the measurement volume. Reducing the flow number below a certain limit leads to an abrupt increase of the swirl boundary layer thickness and therefore to an abrupt increase (steep slope) of the measured swirl component with decreasing flow number. It is remarkable that the effect can be measured on different wall distances at the same flow number. The steep slope indicates the flow separation. The flow number of the upper corner of the steep slope marks $\varphi_{\text{c, min}}$, the lower corner marks $\varphi_{\text{c, max}}$. The separation of the flow is assumed as a span between $\varphi_{\text{c, min}}$ and $\varphi_{\text{c, max}}$. The critical flow number $\varphi_{\text{c}}$ is defined as the flow number where the steep slope reaches $u_\varphi(\varphi_{\text{c, min}})/2$.

Fig. 17: Measured swirl velocity varying radial positions of the measurement volume and flow number with setup II.
In Fig. 18 the swirl velocity distribution for particular flow number is shown, whereby the starting recirculation at the identified critical flow number can be observed. The results of the LDA measurement in Fig. 19 show that an increasing Reynolds number causes a decrease of the critical flow number.

Fig. 19: LDA measurement of swirl velocity vs. Reynolds number and flow number, with setup II.

Fig. 20: Measured critical flow number vs. Reynolds number.

7 CONCLUSION

The investigation shows that even in this most generic form of the inlet of a turbomachine a wall stall similar to the part load recirculation occurs. Particular is that the critical value of the flow number for its onset lies within the practical relevant parameter field for turbomachinery. The wall stall is induced by the positive pressure gradient due to the evolution of the swirl boundary layer. To describe the swirl boundary layer in the transition section of a rotating pipe, we can figure out the following three statements:

1. The swirl boundary layer thickness depends on the Reynolds number, the flow number and the degree of turbulence. Its evolution follows the power law

   \[ \delta_z = C_5(Tu) \varphi^{m_1} Re^{m_2} z^{m_3}. \]

   With use of the experimental data the exponents are determined to \( m_1 \approx -0.44 \pm 0.05 \), \( m_2 \approx -0.48 \pm 0.05 \), \( m_3 \approx 0.44 \pm 0.05 \). The constant \( C_5 \) depends on the degree of turbulence and the pre flow conditioning.

2. The swirl velocity distribution in the transition section is self-similar and follows a progression that is scaled by the boundary layer thickness

   \[ u_\psi(\eta) = (1 - \eta)^k, \]

   with the generalized coordinate \( \eta = y/\delta_z \). The analysis of the measurement shows a constant exponent \( k \approx 1.85 \pm 0.15 \) in reference to the measurement accuracy and the concerned parameter field.

3. When the flow number is reduced below a critical value, the boundary layer separates in the rotating pipe. This critical flow number decreases with increasing Reynolds number and depends on the turbulence of the inlet flow. The critical flow number is the lower limit for the validity of the shown progression of swirl boundary layer thickness and swirl velocity distribution.

Remarkable is that the examined exponent \( k = 1.85 \pm 0.15 \) for the swirl velocity distribution in the transient section is smaller than the value of \( k = 2 \) in the saturated section [7], [20], but
still within range of measurement accuracy. In this context it is necessary to consider that the axial velocity must transform its distribution while passing the transition section to develop the parabolic distribution in the saturated section also [19]. Hence we can obtain that the influence of the axial velocity profile, the changeover of the profile during the transition section and the turbulence in the pre flow need to be further investigated. A further target is to increase the accuracy in the traversing, to reduce the uncertainty of the examined exponents. For axial flow, it is also well known, that roughness will influence the velocity distribution. Its influence on the swirl velocity distribution is content of our further research.

In our further work we will give an analytical description of the swirl boundary layer. Therefore we use integral methods of boundary layer theory from von Kármán and Pohlhausen. We apply a generalization on the equation of momentum of the axial boundary layer, which includes the conservation of angular momentum. With this generalization we can predict the swirl boundary layer thickness and also its interdependency with the axial boundary layer. The shown measurements of the self-similarity and boundary layer thickness will be used for the determination of the circumferential shear stress and swirl velocity distribution in our analytical model. Finally our work will provide a fundamental contribution for a physical understanding of swirl caused wall stall.

REFERENCES