Instabilities at the Inlet of a Rotating Pipe

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Long Abstract

Introduction

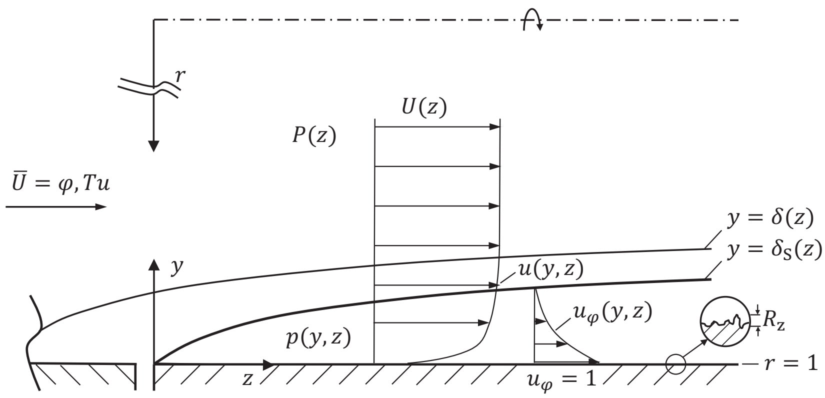

Figure 1. Flow at the inlet of a rotating pipe.

When a fluid enters a rotating circular pipe an angular momentum or swirl boundary layer with thickness of δ_S appears at the wall and interacts with the axial momentum boundary layer with thickness of δ. In the center of the pipe the fluid is free of swirl and is accelerated due to axial boundary layer growth, see figure 1. Below a critical flow number $\varphi := \bar{\tilde{U}}/\tilde{R}\tilde{\Omega} < \varphi_c$, with average axial velocity $\bar{\tilde{U}}$ and circumferential velocity of the pipe $\tilde{R}\tilde{\Omega}$, there is flow separation, known in the turbo machinery context as part load recirculation.

To investigate the turbulent flow at the inlet of a rotating pipe, Laser Doppler Anemometry is used to measure the circumferential velocity profile. By doing so, the swirl boundary layer thickness is measured and follows a power law taking Reynolds number $Re := 2\tilde{R}^2\tilde{\Omega}/\tilde{\nu}$ with the kinematic viscosity $\tilde{\nu}$ and flow number into account. At the inlet the axial boundary layer is turbulent and the growth of the swirl boundary layer is similar to the case when a laminar flow enters the rotating pipe. A critical combination of Reynolds, flow number and axial position causes an instability of the swirl boundary layer development. At this critical combination the swirl boundary layer thickness and the degree of turbulence increase although the axial boundary layer is still turbulent. The critical inlet length when the instability appears and how the swirl boundary develops is to analyze.

1. Methods

Numerically, experimental and analytically investigations analysis the development of the swirl boundary layer and flow separation at the inlet of a rotating pipe depending on the inlet conditions [1–4]. There, the centrifugal force interacts with the axial momentum and the swirl boundary layer thickness follows a power law

$$\delta_S \sim Re^{-0.48\pm0.05}\varphi^{-0.44\pm0.05}z^{0.44\pm0.05}. \quad (1)$$

This relation is valid at high flow numbers independent of laminar or turbulent flow [2, 3]. The flow is axiomatic described by using the integral method of the boundary layer theory and the familiar von Kármán momentum equation is generalized taking the centrifugal force into account. The solution is validated by experiments and the influence of roughness is shown [3, 4]. With Stratford's method [5] a point of incipient separation is derived analytically and validated by experiments [4].

Nishibori et al. [6] measured a laminar to turbulent transition for a laminar flow entering a rotating pipe. In our experiments we observe a second instability in the turbulent regime which is presented within this paper, see figure 2. A free stream channel with a radius of $\tilde{R}$ = 25 mm with air is used to investigate the instability of the swirl boundary layer, whether it appears and how the swirl develops. A thin (configuration I) and a fully developed (configuration II) turbulent axial boundary layer is prepared at the inlet of a rotating pipe. The Reynolds and the flow number vary independent by the rate of rotation and of flow. The instability depends on these parameters and the configurations.

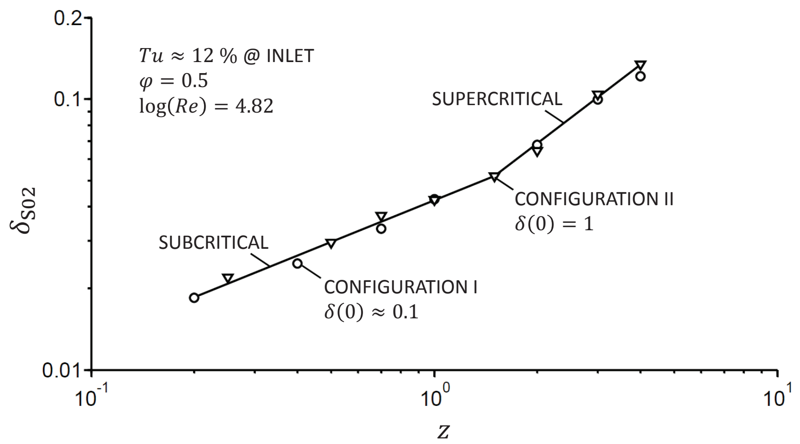

Figure 2. Instability of the swirl boundary layer with a turbulent flow at the inlet of a rotating pipe.

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References

[1] D. Stapp, P.F. Pelz, and J.M. Loens. On part load recirculation of pumps and fans - a generic study. In *Proceedings of the 6th International Conference On Pumps an Fans with Compressors and Wind Turbines*, page 022003, 2013.

[2] D. Stapp and P.F. Pelz. Evolution of swirl boundary layer and wall stall at part load - a generic experiment. In *Proceedings of ASME Turbo Expo GT2014–26235*, 2014.

[3] D. Stapp. *Experimentelle und analytische Untersuchung zur Drallgrenzschicht*. Forschungsberichte zur Fluidsystemtechnik, 2015.

[4] D. Stapp, F.-J. Cloos, and P.F. Pelz. Swirl boundary layer and flow separation at the inlet of a rotating pipe. *submitted to J. Fluid Mech.*, 2014.

[5] B.S. Stratford. The prediction of separation of the turbulent boundary layer. *J. Fluid Mech.*, 5:1–16, 1959.

[6] K. Nishibori, K. Kikuyama, and M. Mirakami. Instability of laminar boundary layer in an axially rotating pipe. In *9th Australasian Fluid Mechancis Conf*, pages 211–214, 1986.