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Two Turbulent Flow Regimes at the Inlet of a Rotating Pipe

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Abstract

When a fluid enters a rotating circular pipe a swirl boundary layer with thickness of $\tilde{\delta}_S$ appears at the wall and interacts with the axial momentum boundary layer with thickness of $\tilde{\delta}$. We investigate the turbulent flow applying Laser-Doppler-Anemometry to measure the circumferential velocity profile at the inlet of a rotating pipe. The measured swirl boundary layer thickness follows a power law taking Reynolds number and flow number into account. A critical combination of Reynolds number, flow number and axial position causes a transition of the swirl boundary layer development in the turbulent regime. At this critical combination, the swirl boundary layer thickness as well as the turbulence intensity increase and the latter yields a self-similarity. The circumferential velocity profile changes to a new presented self-similarity. A method is established to define the transition inlet length, when the transition appears and a stability map for two regimes is given.

Keywords

Boundary Layer — Transition — Rotating Pipe — Swirl Boundary Layer — Turbulent Flow Regimes

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INTRODUCTION

The interdependency of axial momentum and swirl becomes obvious at part load of a turbo machine. At part load below a critical flow number $\varphi := \tilde{\bar{U}}/(\tilde{R}\tilde{\Omega}) < \varphi_c$, with the average axial velocity $\tilde{\bar{U}}$ and circumferential velocity of the pipe $\tilde{R}\tilde{\Omega}$, the swirl causes separation [1,2], the so called part load recirculation. We use a generic model of a turbo machine to investigate the evolution of the swirl and the impact of the swirl on the axial momentum balance; see Fig. 1. When an axial flow enters a pipe, an axial boundary layer with a thickness of $\tilde{\delta}$ appears and develops. By rotating the pipe, a second boundary layer in circumferential direction is produced by viscosity and develops, the so called swirl boundary layer having a thickness $\tilde{\delta}_S$; see Fig. 1. Thus, close to the wall there is a region with a circumferential velocity component $\tilde{u}_\phi$. Due to centrifugal force, there is a non-negligible radial pressure distribution inside the swirl boundary layer for $\varphi \ll 1$ [1,2]. Outside the swirl boundary layer, the flow is swirl-free. Outside the axial boundary layer, the flow is irrotational and the flow is accelerated due to the axial boundary layer growth. The evolution of both boundary layers depends on the Reynolds number $Re := 2\tilde{R}^2\tilde{\Omega}/\tilde{\nu}$, with the kinematic viscosity $\tilde{\nu}$, the flow number φ and the averaged surface roughness $\tilde{R}_z$.

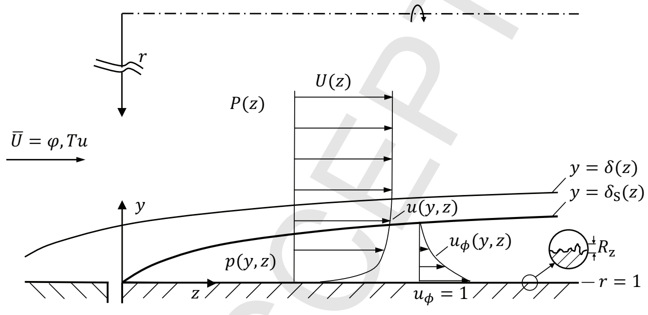

Figure 1. Inlet of a rotating pipe.

In this paper we present the experimentally investigated evolution of the swirl boundary layer and the circumferential velocity profile at high Reynolds numbers as well as high flow numbers in a rotating pipe. A critical combination of Reynolds number, flow number and axial position $(Re, \varphi, z)_t$ causes a transition of the swirl boundary layer development and a transformation of the circumferential velocity profile in the turbulent regime. We are looking for whether and where the transition appears by measuring the circumferential velocity component by Laser-Doppler-Anemometry (LDA). By doing so, we have two different inlet conditions, a thin (configuration I) and a fully developed (configuration II) turbulent axial boundary layer at the inlet of the rotating pipe. Throughout this investigation, we non-dimensionalize length with the pipe radius $\tilde{R}$ and velocities with the pipe circumferential velocity $\tilde{R}\tilde{\Omega}$. The superscript "~" indicates dimensional symbols.

This paper is organized as follows: first, we give a literature review concerning the main investigations of flow in a rotating pipe. In the second section, the experimental methodology is described including the test-rig and the measurement uncertainty. The measurements done with this experimental set-up are presented in section 3 including the circumferential velocity profile, swirl boundary layer thickness and turbulence intensity. Section 4 serves to discuss the results concerning the actual state of the research, presented in section 1. In