ARTICLE IN PRESS

International Journal of Heat and Fluid Flow xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

The capability of large eddy simulation to predict relaminarization

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ARTICLE INFO

Keywords:
Boundary layer
Relaminarization
CFD
RANS
LES

MSC:
00-01
99-00

ABSTRACT

The boundary layer which represents the narrow zone between a solid body and the free stream can have a laminar or a turbulent state. This state influences on the one hand the properties of the near-wall flow like skin friction or heat transfer and on the other hand also the free-stream flow itself, e.g. the downstream flow angle of a turbomachinery blade. Thus it is important for designers of fluid machinery to understand and predict the state of the boundary layer as well as the transition processes between the two states.

In this work the so-called relaminarization is investigated which represents a reverse transition from a turbulent to a laminar boundary layer. At the Institute for Thermal Turbomachinery and Machine Dynamics at Graz University of Technology a test bench has been designed in order to produce a highly accelerated flow, thus triggering relaminarization. In the present work, the flow in this test bench is numerically investigated with Reynolds-averaged Navier-Stokes (RANS) flow simulation as well as with a large eddy simulation (LES).

An outcome of this paper is, that the LES shows a very good agreement to the measurement results and is capable of predicting relaminarization.

1. Introduction

In flows along solid body surfaces, the boundary layer represents the narrow zone between the wall and the free stream where viscous effects are important. Its state of flow (laminar or turbulent) may have strong impact on transport processes like wall friction and heat transfer. These processes influence the efficiency as well as the thermal stress, for example of a turbine blade, and may affect other flow characteristics in the machine as well (see e.g. Bader and Sanz (2015b)).

Many parameters, like free-stream velocity, acceleration, free-stream turbulence etc., may have an influence on the state of a boundary layer. At the first contact of a flowing fluid with a stationary structure the boundary layer flow is laminar before it develops via a transitional zone to become turbulent. The boundary layer passes through several stages within this transitional zone before becoming fully turbulent. Schlichting and Gersten (2006) extensively discussed these different stages.

It is vitally important to understand the influences of key parameters on the onset position and length of the transitional zone in order to predict and potentially control the state of the boundary layer. In turbomachinery, the efficiency of blades and stages may be improved considering transition. This may allow the overall machine performance to be enhanced. In 1991 Mayle (1991) published a comprehensive review of the importance of transition in gas turbines. He analyzed experiments performed by several research groups in order to find the influence of different flow parameters on the transition process.

Since then additional experiments were performed by other research groups. Yip et al. (1993) performed in-flight measurements, where they detected transition with the help of Preston tubes and analyzed the influence of the flight conditions on the boundary layer along an airfoil. Oyewola et al. (2003) and Oyewola (2006) showed how the flow in the boundary layer can be measured with hot-wire anemometry and Laser-Doppler anemometry (LDA), respectively. Widmann et al. (2012) performed near-wall measurements with particle image velocimetry (PIV). Hot-film measurements in the boundary layer were performed, e.g., by Mukund et al. (2012); Preston-tube and thermographic measurements by Bader and Sanz (2015a). Additionally, Bader et al. (2016b) used laser interferometric vibrometry (LIV) to predict transition.

So far, only the transition from laminar to turbulent flow was described. Under certain flow conditions (like strong acceleration), however, a reverse transition or relaminarization from turbulent to laminar can occur. Up to now, only few measurements on relaminarization were reported (e.g. Narasimha and Sreenivasan (1979); Escudier et al. (1998); Mukund et al. (2006)). Therefore, at the Institute for Thermal Turbomachinery and Machine Dynamics of Graz University of Technology a project was launched in order to understand the process of relaminarization and its phases even further and verify common

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.09.008
Received 29 April 2017; Received in revised form 11 September 2017; Accepted 14 September 2017
0142-727X/

Please cite this article as: Bader, P., International Journal of Heat and Fluid Flow (2017), http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.09.008

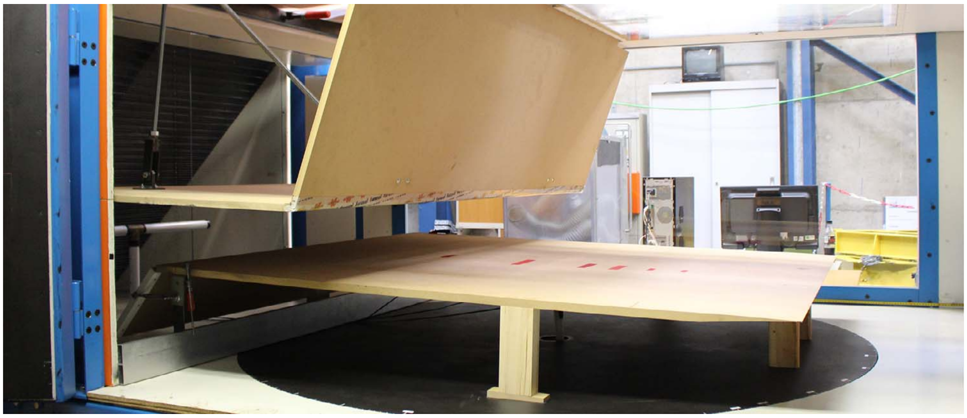

Fig. 1. Photograph of the test bench, flow from right to the left.

threshold values for relaminarization.

Experiments showed four different phases in relaminarization caused by acceleration (Narasimha and Sreenivasan, 1979; Escudier et al., 1998; Mukund et al., 2006; Ichimiya et al., 1998): In the first phase at the beginning of the acceleration zone, the skin friction increases along with a decrease of the shape factor H (ratio of displacement thickness to momentum thickness).

The second phase already shows the first signs of relaminarization, characterized by a breakdown of the law of the wall. Also, the boundary layer becomes thinner. Additionally, the local skin friction coefficient c_f' starts to decrease and the shape factor H starts to rise. The authors state that this second zone is relatively short, within $x/\delta(x) = 20$ to 30 ($\delta(x)$ is the boundary layer thickness). Narasimha and Sreenivasan (1979) described the turbulent velocity fluctuations as "frozen" within this zone. These fluctuations promote a fast re-transition into a turbulent boundary layer in the third phase when the acceleration falls below a certain threshold. Finally, in the fourth phase the boundary layer is turbulent again.

Since the interest of this work is to investigate relaminarization at high acceleration, a test bench with a strongly convergent cross section is needed, leading to a small channel cross section at the outflow. In such a small flow area probes like Preston tubes and hot wire probes can influence the flow considerably. Therefore, non-invasive techniques, such as Laser-Doppler anemometry, are used for measuring the state of the boundary layer.

In this paper, the results of these measurements by Bader et al. (2016a) are used to validate the simulation results. The numerical calculations presented here were done with a traditional RANS approach and a large eddy simulation (LES).

Within the present work, also different numerical approaches were tested regarding their capability of predicting relaminarization. The results of these numerical studies are instrumental in getting a better understanding of the process of relaminarization and re-transition.

In the following section, the numerical setup together with the methodology used for the CFD simulations is discussed. Thereafter a discussion of the results is given, where the RANS and LES data are compared to experimental results. The paper ends with a summary and conclusion.

2. Numerical setup and methodology

The test bench numerically investigated is a closed-loop Göttingen-type wind tunnel at the Institute of Fluid Mechanics and Heat Transfer of Graz University of Technology which delivers air to the test section through several rectifiers and a turbulence grid. Approximately 1200 mm downstream of the turbulence grid, the first measurement plane is situated which also represents the inlet of the computational domain. Therefore all necessary inlet conditions for the simulation are measured at this position. The leading edge of the measurement plate is situated about 1350 mm downstream of the numerical inlet. Along this plate, Laser-Doppler measurements have been performed. In order to have a fully turbulent boundary layer upstream of the acceleration area, a tripwire is mounted at the plate at about $x = 350\ mm$ downstream of the leading edge. A picture of the measurement plate including the acceleration board is given in Fig. 1. The reduction of the flow cross section starts at $x = 810\ mm$ and ends at $x = 1025\ mm$. A small gap is arranged between the outer wall and the acceleration board in order to reduce the corner vortex there.

As mentioned above, the experimental results of LDA measurements are compared with the numerical data calculated with RANS and LES. Bader et al. (2016a) discuss the measurement results together with more details of the setup of the experiment; so the interested reader is referred to their paper.

The numerical results discussed in this paper have been computed with ANSYS® Fluent® v15.0. The first step was a Reynolds-averaged Navier-Stokes (RANS) simulation with the SST $k - \omega$ turbulence model by Menter (1994) as a turbulent reference case. The extension with the $\gamma - Re_\theta$ transition model (Menter et al. 2006) was additionally applied since it has already shown good results in predicting relaminarization (see e.g. Bader and Sanz (2015b); Bader et al. (2017)). The three-dimensional mesh shown in Fig. 2a covers the complete domain of the test section and consists of approximately 35 million nodes ("RANS mesh"). The wall distance of the first grid cells y^+ was kept between 0.1 and 1 in order to resolve the laminar sublayer. The boundary conditions at the inlet and outlet have been taken from the experiment.

Results of the RANS simulation were extracted at three lines marked with their corresponding letter in Fig. 2a: (a) a line from the leading edge of the plate towards the top wall, (b) a line from the trailing edge of the plate towards the parallel plate and (c) a line in the gap between the acceleration board and the outer wall. These lines mark the geometrical boundaries of the LE simulation and the RANS flow variables extracted from these lines are used as inlet and outlet conditions. This resulting smaller domain with a reduced width of $z = 80\ mm$ is shown in Fig. 2b and consists of approximately 66 million nodes ("LES mesh"). The simulations show that about 20 structures evolve at the trip wire in spanwise direction so that an influence of the spanwise confinement is not expected. For the large eddy simulation the flow regime is divided into a coarse and a dense mesh which interact with each other. The finer domain is situated close to the wall starting upstream of the trip wire and has a height of $y = 40\ mm$, whereas the coarser domain covers the free-stream flow. This division of the domain can be seen in Fig. 3. Also the tripwire which generates the turbulence within the boundary layer is clearly apparent in the zone with the denser mesh. The dimensions of the wall cells for the three coordinates x^+,z^+ and y^+ are about 4.8, 4.7 and 0.6 respectively, at a representative position at $x = 695\ mm$.

The time step for the LE simulation has been set to $\Delta t = 2{\cdot}10^{-5}\ s$, thus resolving frequencies up to $f = 50,000\ Hz$. To reduce the