INTERPRETATION OF THE MECHANISM RESPONSIBLE FOR THE PERSISTENCE OF A LAMINAR REGION IN TURBULENT DUCT FLOW

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Abstract The flow field in an isosceles triangular duct with a small apex angle of $11.5°$ is investigated using direct numerical simulation at the hydraulic Reynolds number $Re_h = 4500$. Within the duct cross-section regions with essential laminar and turbulent properties are found to exist next to each other. From analysis of this flow field we gain insights into the mechanisms responsible for the flow laminarisation towards the corner of the duct, which leads to a significant reduction of the skin friction. In addition, further investigations of the disturbances appearing in the laminar part of the flow domain indicate a possible application of corners for the delay of laminar to turbulent transition in duct flows.

INTRODUCTION

The flow in an isosceles triangular duct with a small apex angle of $11.5°$ was investigated experimentally by Eckert and Irvine [1, 2]. Their studies were mainly motivated by the observation of critically high temperatures in narrow passages of heat exchangers. Using flow visualization techniques the authors observed laminar and turbulent flow to coexist for a certain range of hydraulic Reynolds numbers where the flow usually can be expected to be fully turbulent. In the context of today's efforts towards saving energy this observation is of particular interest as the resistance in laminar flows is significantly reduced compared to the turbulent regime. In order to gain further insights into the flow field, we perform direct numerical simulations (DNS) of the triangular duct investigated experimentally by Eckert and Irvine [1, 2] and related duct geometries.

PROCEDURE

As the triangular duct has a very small apex angle of $11.5°$ it is straightforward to spatially discretize the domain with an unstructured grid consisting of prism layers close to the wall and a polyhedral core mesh. A sketch of the computational domain is shown Figure 1. The grid is extruded in streamwise (x_1) direction. The total streamwise extension is set to $L_{x_1} = 5\,D_h$ with a constant grid spacing of $\Delta x_1^+ = 9.5$. The wall-normal grid spacing is chosen to ensure $\Delta x_{2,3}^+ \leq 1.6$ at the wall and $\Delta x_{2,3}^+ \leq 5$ in the center resulting in $3.76 \cdot 10^6$ cells in total.
The simulation is carried out under constant flow rate condition. Time discretization is achieved using a second order implicit scheme and the time step is chosen to ensure a Courant number of $Co_{max} < 0.2$. Time averaging is performed for 35 turnover times. In addition, the results are spatially averaged in the homogeneous streamwise direction.

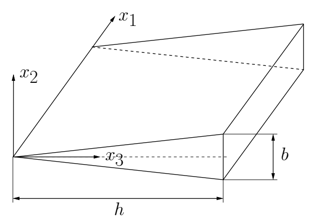

Figure 1: Sketch of the computational domain. x_1: streamwise direction

RESULTS

The numerical results show the coexistence of turbulent flow and a flow region having essentially laminar properties, which is located close to the small apex angle resulting in a decrease of the flow resistance of about 20% compared to the corresponding result of the Blasius correlation [9]. Eckert and Irvine [1] suggest to characterize the spanwise extension of the laminar regime using two different criteria: an 'instability line' which represents the position where the first fluctuations are observed and a 'transition line' which shows the position of starting deviation of the velocity profiles from the parabolic laminar one. These experimentally determined lines are included in Figure 2 together with the DNS results for the rms-values of the velocity fluctuations along the x_3-axis. Close to the right side of the triangle ($x_3/h = 1.0$) the development of $u_{i,rms}$ resembles that observed for the flow through a square duct along the wall bisector at a similar Reynolds number [4]. Moving in negative x_3-direction $u_{2,rms}$ falls below $u_{3,rms}$, indicating the damping character of the corner region in x_2-direction. This behaviour is followed by a continuous decrease of both quantities. Beyond the transition line, the turbulent intensities decrease to very small values and a pure laminar parabolic velocity profile is found. In Figure 2 we also include the second invariant of the anisotropy tensor [8], II_a, which expresses the magnitude of the turbulent anisotropy and can be linked to drag reduction in turbulent flows [3]. Starting from the right and moving in negative x_3-direction towards the transition line, a significant increase of II_a can be observed. This observation is complemented by plotting the trajectories along the x_2-direction at different spanwise positions in the anisotropy-invariant map (Figure 3). It can be seen that the anisotropy increases not only in the center ($x_2 = 0$) but for the entire duct height when moving towards the triangle corner. This tendency of increased near-wall anisotropy is characteristic for a group of turbulent drag reduction mechanisms [3] and can be related to a reduction of the turbulent dissipation rate at the wall if the fluctuating component in the mean flow direction is the dominant one [6].

In the laminar corner region of the duct the development of II_a can be used to characterize the anisotropy of the disturbances. For $x_3/h = 0.0$ the disturbances reach the state of maximum anisotropy, e.g. the one-component (1C) limit. When moving in positive x_3-direction away from the edge, the anisotropy is observed to decrease continuously until a local minimal value is reached, which coincides with the instability line. A similar behaviour is also observed in other duct geometries containing a coexisting laminar and turbulent region, e.g. a triangular duct with an apex angle of 4° and a diamond-shaped duct. Both will also be presented at the conference. This indicates that highly anisotropic disturbances are characteristic for the stable laminar region, which is in agreement with findings of Jovanović et al [5] in respect to the anisotropy of free-stream disturbances for the persistence of laminar flow along a flat plate.

The observations in the development of II_a indicate that high anisotropy in the Reynolds stresses enforced to the flow through geometrical constraints can initiate reverse transition and thus drag reduction in the turbulent regime. At the same time, highly anisotropic disturbances are characteristic for the stable laminar region. The present results suggest that duct flow geometries which promote anisotropy, either of turbulent fluctuations or of disturbances in a laminar flow, are likely to result in a delay of laminar to turbulent transition or in drag reduction in the fully turbulent regime [7] even if the extreme geometric constraints that lead to a coexistence of laminar and turbulent flow in a duct are not fulfilled.

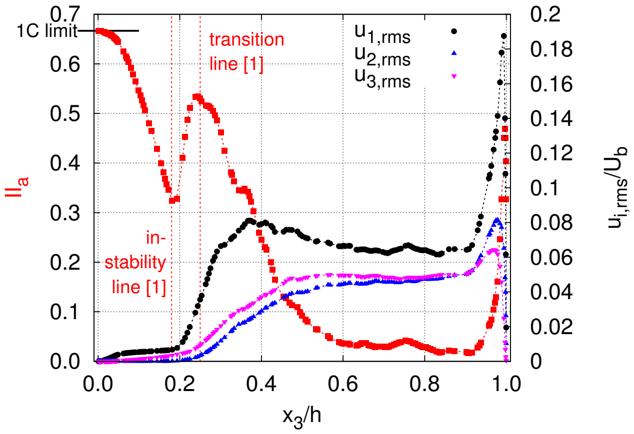

Figure 2: Development of the second anisotropy invariant, II_a, and the normalized rms-values of the velocity fluctuations, $u_{i,rms}$, along the x_3-axis (note: irregularities in the data result from the nature of the unstructured grid and the presently limited spatial interpolation of the data).

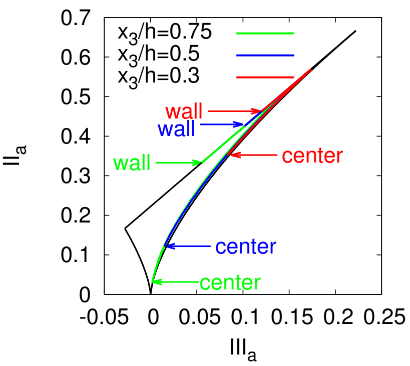

Figure 3: Trajectories in the anisotropy invariant map at three spanwise positions in the triangular duct.

References

[1] E. Eckert and T. Irvine. Flow in corners of passages with noncircular cross sections. *Trans. ASME*, **78**(4):709–718, 1956.

[2] E. Eckert and T. Irvine. Pressure drop and heat transfer in a duct with triangular cross section. *J. Heat Transfer*, pages 709–718, 1960.

[3] B. Frohnapfel, P. Lammers, J. Jovanović, and F. Durst. Interpretation of the mechanism associated with turbulent drag reduction in terms of anisotropy invariants. *J. Fluid Mech.*, **577**:457–466, 2007.

[4] S. Gavrilakis. Numerical simulation of low-reynolds-number turbulent flow through a straight square duct. *J. Fluid Mech.*, **244**:101–129, 1992.

[5] J. Jovanović, B. Frohnapfel, E. Škaljić, and M. Jovanović. Persistence of the laminar regime in a flat plate boundary layer at very high reynolds number. *Thermal Sci.*, **10**:63–96, 2006.

[6] J. Jovanović, M. Pashtrapanska, B. Frohnapfel, and F. Durst. On the mechanism responsible for turbulent drag reduction by dilute addition of high polymers: Theory, experiments, simulations, and predictions. *ASME J. Fluids Eng*, **128**:118–130, 2006.

[7] P. Lammers, J. Jovanović, B. Frohnapfel, and A. Delgado. Erlangen pipe flow: the concept and dns results for microflow control of near-wall turbulence. *Microfluidics Nanofluidics*, pages DOI 10.1007/s10404–012–0972–0, 2012.

[8] J. Lumley and G. Newman. The return of isotropy of homogeneous turbulence. *J. Fluid Mech.*, **82**:161–178, 1977.

[9] H. Schlichting. *Boundary-layer theory*. McGraw-Hill Book Company, New York, 7th edition, 1979.