Prediction of Laminar-Turbulent Transition on an Airfoil at High Level of Free-Stream Turbulence

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ABSTRACT

This paper is focused on measurements and prediction of laminar-turbulent transition at high free-stream turbulence in boundary layers of airfoil geometries with external pressure gradient changeover. Experimental and numerical study is performed for a number of flow cases covering a range of flow Reynolds numbers, turbulence intensities and pressure gradient distributions. The flow parameters in experiments and computations are typical for turbomachinery applications and main motivation of current study is validation of transition models which can be used for transition prediction in such engineering applications. In current work the experimental data are used to validate a transition model by Langtry and Menter which showed good agreement with experiments for all test cases.

1 INTRODUCTION

Laminar-turbulent transition has significant importance in aerodynamics by affecting evolution of losses, appearance of separation and stall. The boundary layer state has dominant effect on the distribution of wall shear stress and surface heat transfer. To predict and manage turbulence in different flow cases is beneficial for optimum advantage, namely, to reduce it when it is harmful (e.g. to decrease the skin friction or heat transfer) and to increase it when it is desirable (to avoid flow separation). The prediction of laminar-turbulent transition at high free-stream turbulence is specifically of great importance in turbomachinery where the boundary layer state defines the blade heat transfer and flow separation margins. However it is well-known that prediction of transition is particularly challenging task for turbulence modelling. A number of turbulence models claim possibility of transition prediction and none of them is proven to be flawless so far. A transition model suggested by Menter et al. [1] is based on correlation-based approach and appears to provide consistent results. This model has been applied to several 2D and 3D test cases by the same research group [2] and simulations agreed well with experiments for all test cases at wide range of Reynolds numbers and freestream turbulent intensities. The literature survey shows though that surprisingly few other validation cases of this model are publicly available. To fulfil this gap and to validate applicability of the Langtry and Menter model for turbomachinery applications was the main purpose of current study.

2 EXPERIMENTAL AND NUMERICAL SETUP

Experiments were carried out in a wind tunnel facility of Chalmers University. Tests were performed on specially designed airfoil models of large scale for obtaining thick boundary layers which enabled to conduct detailed measurements in the boundary layers. The tunnel is of open circuit blower type and was operated at velocities between 5 and 18 m/s. The cross section of the facility is 200 by 1200 mm. The tunnel test section is equipped with an end-wall boundary-layer suction system for controlling the flow two-dimensionality. A turbulence grid is used to create two different turbulence intensities for tests: 2% and 4%. The measurements were done by a hot-wire anemometer. Probe positioning and data acquisition were fully automated.

As mentioned, the numerical calculations were performed with the Gamma-Theta transition turbulence model by Langtry and Menter [1]. This correlation-based model uses transport equations for intermittency and momentum thickness Reynolds number. The intermittency equation is coupled with Menter's $k — \omega$ SST model and used to turn on the production of turbulent kinetic energy beyond the turbulent transition region. The second transport equation is formulated in terms of the momentum thickness Reynolds number at transition onset. An empirical correlation is used to control the transition onset criteria in the intermittency equation.

Steady two-dimensional computations were performed by using pressure based implicit finite volume solver and second-order discretization of equations. The computational domain consisted of 10^5 quadrilateral cells with an O-grid surrounding the model and had resolved near-wall layer (with $y^+<0.5$). Grid independency was checked for 6 selected cases by refining and coarsening the grid. Boundary conditions in numerical calculations are carefully matched with corresponding conditions from the wind tunnel tests. At the inlet the velocity, turbulence intensity and inlet turbulent length scale are set as in experiments.

To investigate different pressure gradient distributions totally 4 different geometries were studied. The model shapes were based on two modifications of NACA6 airfoil at two different aspect ratios, see Figure 1. Experimental and numerical data were collected for totally 16 flow cases with different flow Reynolds number, turbulence intensity and pressure gradient distributions.

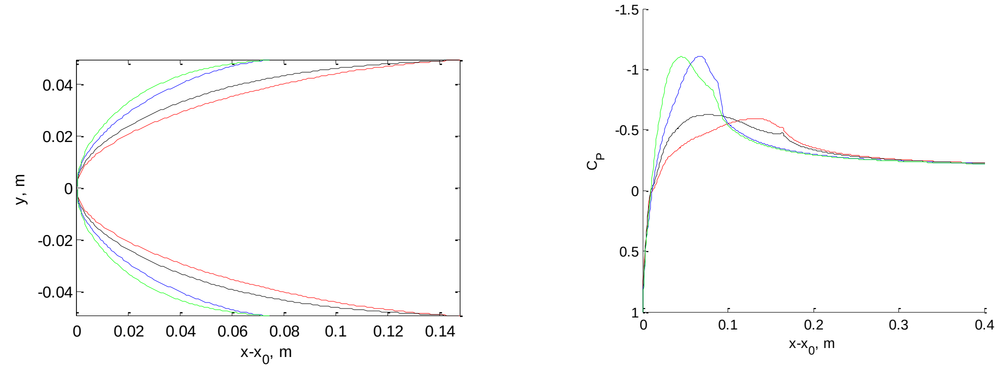

Figure 1: Model geometries and corresponding C_p distributions.

3 RESULTS

In full paper the results of experiments and numerical computations are analysed in detail. The effect of turbulence and pressure gradient on the transition Reynolds number and transition length is discussed. The results of experiments are compared to previous commonly accepted experiments. Comparison between the experiments and numerical simulations by Langtry and Menter model is performed. The results are encouraging and CFD calculations show rather good prediction of transition location for cases with strong adverse pressure gradient for both studied turbulence levels. In cases of mild adverse pressure gradient CFD computations demonstrate a satisfactory prediction with some over-prediction of the transition onset. In opposite, the transition is under-predicted for case of transition start in zone of favourable pressure gradient. Figure 3 demonstrates example of good performance of the turbulence model at high Reynolds number (Re_θ= 300-1000), mild pressure gradient and 2% inlet turbulence intensity.

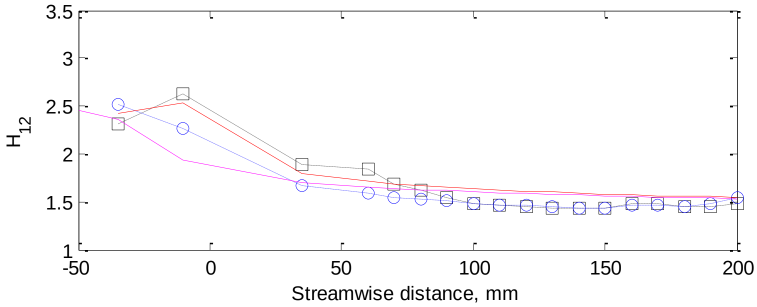

Figure 2: Comparison of boundary layer shape factor from CFD (lines) and experiments (symbols) for two different airfoil models at Tu=2%.

References

[1] Menter, F.R., Langtry, R.B., Likki, S.R., Suzen, Y.B., Huang, P.G., and Völker, S., A Correlation based Transition Model using Local Variables Part 1 – Model Formulation, ASME Paper GT2004-53452, 2004.

[2] Langtry, R.B., Menter, F.R., Likki, S.R., Suzen, Y.B., Huang, P.G., and Völker, S., A Correlation based Transition Model using Local Variables Part 2 – Test Cases and Industrial Applications, ASME Paper GT2004-53454, 2004.