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# TURBINE VANE CASCADE HEAT TRANSFER PREDICTIONS USING A MODIFIED VERSION OF THE $\gamma - \tilde{\mathrm{Re}}_{\theta t}$ LAMINAR-TURBULENT TRANSITION MODEL

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## INTRODUCTION

Numerical simulation of heat transfer influenced by laminar-turbulent transition phenomena is of the great practical interest, especially for gas turbine cascades. For a long time, boundary-layer solvers involving one or another empirically-derived correlation for transition onset were used by engineers for turbine-blade heat transfer prediction. Since the boundary-layer approach has many well-known limitations, today there is a pronounced trend to replace it by computations with advanced Navier-Stokes solvers which incorporate some of differential-equation models for transition prediction. A number of differential-equation transition models suggested in the literature can be divided into two groups. The first group covers the models that do not involve any correlation derived from experiments for transitional boundary layers. Recent examples are the transition calibration of the Menter SST model [Langtry & Sjolander 2002], and the *k-kl-ω* model suggested by Walters and Leylek [2005] and implemented in particular into the ANSYS-FLUENT package. Transitional models belonging to the second group directly use empirical data for transition onset, and because of that they can be treated as potentially more reliable. Among these models, the correlation-based $\gamma - \tilde{\mathrm{Re}}_{\theta t}$ model developed by Menter et al [2004] is of special interest for implementation into modern CFD codes since it does not involve any non-local variables, as compared with some other models of that kind [e.g., Steelant & Dick 2001]. This model has been implemented first into the ANSYS-CFX package, and recently into the ANSYS-FLUENT. A specific situation concerning the original $\gamma - \tilde{\mathrm{Re}}_{\theta t}$ model description was in that two empirically-derived correlations were deemed proprietary and closed for public. However, considering the original model as a framework, there is a possibility to carry out independently the process of calibrating the key correlations (including the two missing) using published data on transitional boundary-layers. It has been demonstrated in particular in a recent work by Malan et al [2009] aimed at implementation of the $\gamma - \tilde{\mathrm{Re}}_{\theta t}$ model into the STAR-CCM+ package. Moreover, essential modifications and additional correlations may be introduced to improve the model accuracy. In the present contribution, a modified version of the $\gamma - \tilde{\mathrm{Re}}_{\theta t}$ model is given together with results of its application to transonic vane cascade heat transfer predictions.

## MODEL DESCRIPTION

The $\gamma - \tilde{\mathrm{Re}}_{\theta t}$ model involves two transport equations additional to the Menter SST turbulence model. The first equation servers to evaluate the intermittency coefficient distribution, and the second one is derived for a special variable that takes the role of the critical boundary-layer momentum-thickness Reynolds number, $\mathrm{Re}_{\theta}$, appearing in an empirically-derived correlation for transition onset. A motivation to modification of the original model has resulted from our experience of its employment, both with the ANSYS-CFX implementation and with the variant implemented into our in-house CFD code after the process of calibrating the missing correlations. Here we briefly describe the primary differences between the original model and the present modification.

First, the diffusion coefficient for the transition onset Reynolds number is increased many times as compared with the original value. Note that in case of the original diffusion coefficient the “diffusing Reynolds number” within the boundary layer is strongly different from the “true” transition onset Reynolds number obtained by the correlation technique, and because of this the local parameters of the external flow (local turbulence intensity and acceleration factor) do not have a proper influence on transition processes in the boundary layer. Second, a special empirical function is introduced to smooth the transition process, since it is typically too fast in case of the original model, as compared with experiments. The third modification consists in introducing a limiting function for the intermittency coefficient dissipation. This is done to improve the model possibility for prediction of transition under conditions of fast local variations of the external flow. In such cases the transition conditions arise only in a short region of the boundary layer and an overextended transition is observed in experiments. In case of the original model, the transition process initiated within the short region may decay completely downstream due to an excessive dissipation of the intermittency coefficient.

## TEST CASES AND RESULTS

The modified version of the transition model has been extensively tested using the experimental data by Arts et al [1990]. In these experiments the two-dimensional transonic flow through a turbine vane cascade was studied for different values of the exit Reynolds number, $Re_2$, the exit Mach number, and the free-stream inlet turbulence intensity, *Tu*. The vane heat transfer was measured whereas the temperature of the inflow was constant for all cases. The present numerical simulation using the in-house CFD code SINF [Smirnov & Zaitsev 2004] was performed for a number of cases which parameters are listed in Table 1. Its last column contains the values of the viscosity ratio which are calculated with the following evaluative formula: $R_{T\,in} = Tu \cdot U_{in} \cdot 0.75d \cdot \nu^{-1} \cdot (2/3)^{-0.5}$, where $d$ is the cross size of the square bars of the grid used for turbulence generation, $U_{in}$ - inflow velocity, $\nu$ - kinematic viscosity. A block-structured grid of H-O-H topology was used in the computations. The O-block covering the vane sub-domain consisted of 12480 cells. The averaged value of $y^+$ for the near-wall cells did not exceed 0.4.

Table 1
Parameters of the Cases computed

| Case | $Re_2$, $\times 10^6$ | $Ma_2$ | *Tu*, % | $R_{T\,in}$ |
|---|---|---|---|---|
| MUR210 | 1.10 | 1.076 | 1.0 | 9 |
| MUR213 | 1.09 | 1.068 | 4.0 | 36 |
| MUR232 | 1.09 | 1.061 | 6.0 | 54 |
| MUR116 | 2.11 | 1.090 | 0.8 | 14 |
| MUR243 | 2.13 | 1.098 | 4.0 | 71 |
| MUR241 | 2.11 | 1.089 | 6.0 | 107 |
| MUR247 | 2.12 | 0.922 | 1.0 | 18 |
| MUR245 | 2.13 | 0.924 | 4.0 | 71 |
| MUR239 | 2.14 | 0.922 | 6.0 | 108 |

Analyzing the transition development on the vane, one should emphasize that the suction-side pressure distributions are considerably different in cases of $Ma_2 \approx 0.9$ and $Ma_2 \approx 1.1$. When $Ma_2 \approx 0.9$, the streamwise pressure gradient is favorable over the most part of the surface. A pressure rise takes place only near the vane trailing edge where a weak shock is observed. In case of $Ma_2 \approx 1.1$, a small region of the adverse pressure gradient is present near the middle of the vane.

Fig. 1 presents a comparison of computed and experimental distributions of the heat transfer coefficient for case of a moderate Reynolds number, $Re_2 \approx 10^6$, under the $Ma_2 \approx 1.1$ conditions. Effect of the free-stream turbulence intensity (*Tu* =1%, 4%, 6%) is analyzed. The coordinate *s* corresponds to the distance along the vane surface starting from the leading-edge stagnation point (positive values - suction side, negative - pressure side). One can see that an strong increase of the heat wall flux, due to turbulence generation, is observed only near the vane trailing edge. In all other regions, the boundary layer remains "pseudo-laminar". The present model gives a good prediction of the heat transfer except the short region near the vane trailing edge.

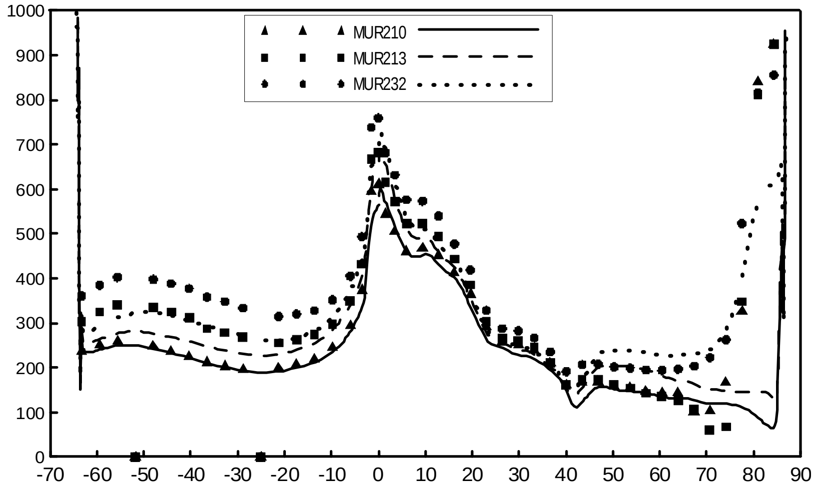


Figure 1. Effect of freestream turbulence intensity on heat transfer coefficient distribution in case of $Re_2 = 10^6$, $M \approx 1.1$. Symbols - experiments, lines – computations .

More challenging are the cases with a higher Reynolds number, $Re_2 \approx 2{\cdot}10^6$. Results obtained for $Ma_2 \approx 1.1$ are given in Fig. 2. On the suction side, the transition begins in the region of adverse pressure gradient, and the model predicts the transition start correctly. In cases of MUR241 and MUR243 the modified model overpredicts the heat flux similar to the original one. Notably also that for a relatively high turbulence intensity, *Tu* = 4 and 6% , the transition occurs on the pressure side as well. The transition is initiated by external turbulence under conditions of favorable pressure gradient; and such a behavior is predicted by the model correctly.

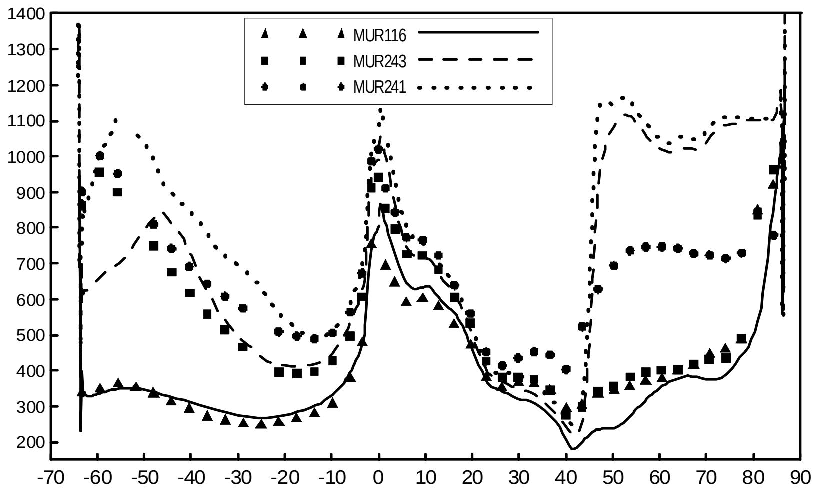


Figure 2. Same as Fig.1 but for $Re_2 = 2 \cdot 10^6$, $M \approx 1.1$.

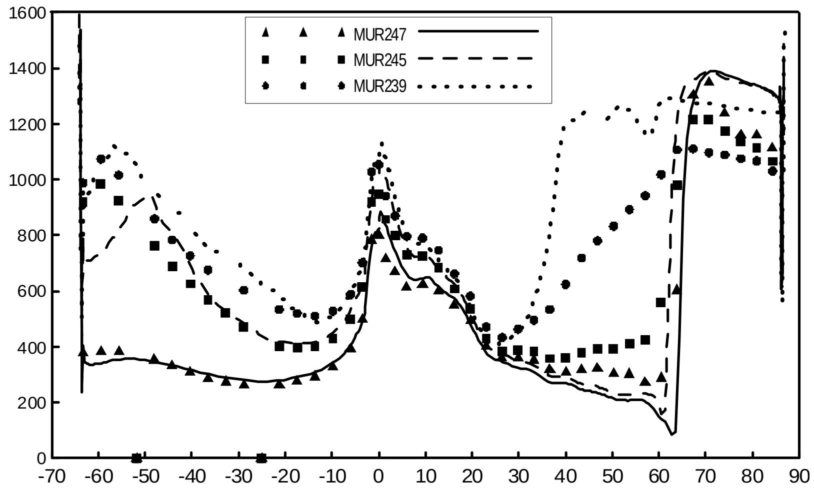


Figure 3. Same as Fig.1 but for $\mathrm{Re}_2 = 2 \cdot 10^6$, $M \approx 0.9$.

The heat transfer distributions computed for $Ma_2 \approx 0.9$. are compared with the measurement in Fig.3. One can see an almost full accordance between the experiments and calculations for the pressure side data and a satisfactory predictions for the suction-side heat transfer.

Note finally, that for all the test cases considered the modified version of the $\gamma$ - $\tilde{\mathrm{Re}}_{\theta t}$ model predicts the vane heat transfer not worse and in the most cases more accurate as compared with the original model. This fact will be illustrated in the full paper.

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