ZÁPADOČESKÁ UNIVERZITA V PLZNI

FAKULTA STROJNÍ

KATEDRA ENERGETICKÝCH STROJŮ A ZAŘÍZENÍ

ZÁPADOČESKÁ UNIVERZITA V PLZNI

POWER SYSTEM ENGINEERING, THERMODYNAMICS & FLUID FLOW

2013

JEDNOTLIVÝ PŘÍSPĚVEK ZE SBORNÍKU

evropský sociální fond v ČR

EVROPSKÁ UNIE

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

OP Vzdělávání pro konkurenceschopnost

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

EFFECT OF FREE STREAM TURBULENCE ON ENERGY LOSSES OF TURBINE BLADE CASCADE

NÁDVORNÍK Michal, STRAKA Petr, PŘÍHODA Jaromír

The contribution deals with the numerical simulation of 2D compressible flow through a linear turbine blade cascade including the laminar/turbulent transition. Predictions accomplished by several transition models for various free-stream turbulence and Reynolds numbers. Calculated values of the loss coefficient and the outlet flow angle were compared with experimental data obtained for the turbine blade cascade VS33 with smooth blades and the relative pitch t/c=0.7.

Keywords: flow through turbine blade cascade, free stream turbulence, transition

Introduction

Flow in turbomachinery especially through blade cascades is influenced by many factors, mainly by the pressure gradient, free stream turbulence, often by the wall roughness. The flow field and consequently energy losses resulting from the numerical simulation of the compressible flow through turbine blade cascades are to a large degree influenced not only by the used turbulence model, but also by the model of the laminar/turbulent transition and by the model of turbulent heat transfer.

At present, the transition models are based either on the algebraic and/or transport equation for the development of the intermittency coefficient in the transition region or on so called three-equation model with the equation for the energy of laminar fluctuations. All models based on the algebraic and/or transport equations for the intermittency coefficient can not do without empirical correlations for the onset and the length of the transition region. The application of so called local variables is necessary for prediction of transitional flows in complex geometries by means of non-structured grids.

The contribution deals with the numerical simulation of 2D compressible flow through a linear turbine blade cascade including the laminar/turbulent transition. Predictions were carried out partly by the in-home numerical code based on the EARSM turbulence model with the algebraic transition model and partly by the commercial software ANSYS Fluent by means of the three-equation k-k_L-ω model. Numerical simulations following up to Nádvorník et al. [1] were accomplished for various inlet free-stream turbulence levels and Reynolds numbers. Results were compared with experimental data obtained for the turbine blade cascade VS33 with smooth blades and the relative pitch t/c=0.7.

2. Mathematical model

The model of compressible turbulent flow described by the continuity equation, the Favre-averaged Navier-Stokes equations, the energy equation, and by the constitutive relations was used for numerical simulations of flow through the turbine blade cascade. The governing equations were closed by the turbulence model and by the transition model. Predictions were carried out partly by the in-home numerical code based on the explicit algebraic Reynolds-stress model according to Hellsten [2] with the algebraic transition model proposed by Straka and

Příhoda [3] and partly by the commercial software ANSYS Fluent by means of three-equation k-k_L-ω model of Walters and Cokljat [4].

The algebraic model was implemented into the in-house numerical code. The code is based on the finite volume method of the cell-centered type with the Osher's-Solomon's approximation of the Riemann solver and a two-dimensional linear reconstruction with the Van Albada's limiter. The governing equations are discretized using a multi-block quadrilateral structured grid with a block overlapping implementation.

2.1 Algebraic transition model

The algebraic transition model is connected with the explicit algebraic Reynolds-stress turbulence model (EARSM) proposed by Hellsten [2]. The Reynolds stress is given by the anisotropy tensor defined by the relation

$$a_{ij} = \frac{\overline{u_i u_j}}{k} - \frac{2}{3}\delta_{ij} \tag{1}$$

The anisotropy tensor is expressed by the polynomial

$$a_{ij} = \beta_1 S_{ij} + \beta_3\left(\Omega_{ik}\Omega_{kj} - \frac{1}{3}\delta_{ij} II_\Omega\right) + \beta_4\left(S_{ik}\Omega_{kj} - \Omega_{ik}S_{kj}\right) + \beta_6\left(S_{ik}\Omega_{kl}\Omega_{lj} + \Omega_{ik}\Omega_{kl}S_{lj} - \frac{2}{3}\delta_{ij} IV\right) + \beta_9\left(\Omega_{ik}S_{kl}\Omega_{lm}\Omega_{mj} - \Omega_{ik}\Omega_{kl}S_{lm}\Omega_{mj}\right) \tag{2}$$

The non-dimensional strain-rate and vorticity tensors are defined by relations

$$S_{ij} = \tau\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \text{ and } \Omega_{ij} = \tau\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right) \tag{3}$$

The time scale τ is given by the relation

$$\tau = \max\left(\frac{1}{\beta^*\omega}; C_\tau\sqrt{\frac{\nu}{\beta^*\omega k}}\right) \tag{4}$$

where the viscous time scale is used near the wall with constants $\beta^* = 0.09$ and $C_\tau = 6$. Coefficients β in Eq.(2) are functions of invariants $II_S = S_{kl}S_{lk}$, $II_\Omega = \Omega_{kl}\Omega_{lk}$, $III_S = S_{kl}S_{lm}S_{mk}$, and $IV = S_{kl}\Omega_{lm}\Omega_{mk}$. The transport equations for the turbulent energy k and the specific dissipation rate ω are given by equations

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = \rho P_k - \rho\varepsilon + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k\mu_t\right)\frac{\partial k}{\partial x_j}\right] \tag{5}$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho U_j\omega)}{\partial x_j} = \rho\frac{\omega}{k}\left(C_{\omega1}P_k - C_{\omega2}\varepsilon\right) + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_\omega\mu_t\right)\frac{\partial\omega}{\partial x_j}\right] + \sigma_d\frac{\rho}{\omega}\max\left(\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j};0\right) \tag{6}$$

These equations are used in the two-layer form with two sets of model coefficients and with the blending function similarly as the BSL and/or SST models proposed by Menter [5]. The detailed description of the EARSM model is given by Hellsten [2]. For the prediction of the transitional flows, the production and destruction terms in the k-equation are multiplied by the intermittency coefficient γ.

The algebraic transition model is based on the concept of different values of the intermittency coefficient in the boundary layer γ_i and in the free stream γ_e. The intermittency coefficient in the boundary layer is given by the relation

$$\gamma_i = 1 - \exp\left[-\hat{n}\sigma\left(Re_x - \mathrm{Re}_{xt}\right)^2\right] \tag{7}$$

proposed by Narasimha [6]. The transition onset is given according to Straka et al. [7] by the empirical correlation for the momentum Reynolds number $Re_{\theta t} = f(Tu, \lambda_t)$ where Tu is the free-stream turbulence level and λ_t is the pressure-gradient parameter. The length of the transition region given by the spot generation rate n and the spot propagation rate σ is expressed using the parameter N introduced by Narasimha [8]. The effect of the free-stream turbulence and the pressure gradient on the parameter N is correlated by an empirical relation $N=f(Tu, \lambda_t)$ proposed for the attached flow by Solomon et al. [9]. The onset and length of transition in separated flow is given by correlations proposed by Mayle [10]. To avoid the application of local variables, the maximum of the vorticity Reynolds number $Re_{\nu max}$ is used instead of the momentum Reynolds number Re_θ. The vorticity Reynolds number is given for complex flows by the relation

$$Re_\nu = y^2 |\Omega| / \nu \tag{8}$$

where y is the distance from the wall and $\Omega=(2\Omega_{ij}\Omega_{ij})^{1/2}$ is the absolute value of the vorticity tensor. This link is expressed by the relation $Re_\theta = Re_{\nu max}/C$ where the parameter C depends on the pressure gradient. The algebraic transition model is described in detail by Straka at al. [7].

2.2 k-k$_L$-ω model

The three-equation model with transport equations for the turbulent kinetic energy k_T, the laminar kinetic energy k_L and the specific dissipation rate ω was proposed by Walters and Cokljat [4]. The model is based on the assumption that velocity fluctuation in the region before the transition can be divided into two parts - partly on small vortices contributing to the turbulence production, and partly on large mainly longitudinal vortices near the wall contributing to the production of non-turbulent fluctuations. The transport equations for the turbulent kinetic energy k_T, laminar kinetic energy k_L and the specific dissipation rate ω are given by

$$\frac{Dk_T}{Dt} = P_{kT} + R_{BP} + R_{NAT} - D_T + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\alpha_T}{\sigma_k}\right)\frac{\partial k_T}{\partial x_j}\right] - \omega k_T \tag{9}$$

$$\frac{Dk_L}{Dt} = P_{kL} - R_{BP} - R_{NAT} - D_L + \frac{\partial}{\partial x_j}\left[\nu \frac{\partial k_L}{\partial x_j}\right] \tag{10}$$

$$\frac{D\omega}{Dt} = C_{\omega 1}\frac{\omega}{k_T}P_{kT} + \left(\frac{C_{\omega R}}{f_w} - 1\right)\frac{\omega}{k_T}\left(R_{BP} + R_{NAT}\right) - C_{\omega 2} f_w^2 \omega^2 + C_{\omega 3} f_\omega \alpha_T f_w^2 \frac{\sqrt{k_T}}{y^3} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\alpha_T}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] \tag{11}$$

These equations contain as the standard turbulence model terms representing the advection, production, diffusion, and destruction. The transition process is express by the energy transfer from the energy of non-turbulent mostly longitudinal fluctuations k_L to the turbulent energy k_T representing the three-dimensional turbulent fluctuations of various length and time scales. The laminar energy k_L is caused by the interaction of non-turbulent velocity fluctuations with the shear flow in the region before the transition region where the turbulent fluctuations are damped. After the transition onset, this damping is restricted to the viscous sublayer. The model is in detail described by Walters and Cokljat [4].

3. Results

The described transition models were applied for the simulation of 2D compressible flow through the turbine blade cascade VS-33 with the relative spacing t/c = 0.7 and the inlet angle $\alpha_1 = 0^o$. The predictions were carried out for the Reynolds numbers Re_{2is} in the range from 2×10^5 to 1×10^7 and for the Mach numbers M_{2is} = 0.5, 0.7, and 0.9. Numerical results were compared with experimental data of Benetka and Kladrubský [11], Benetka et al. [12] and Kladrubský [13].

The computational domain with the inlet in the distance 0.04 m upstream the leading edge of the blade is shown in Fig.1 including the prescription of boundary conditions. For the subsonic flow, the total pressure, the total temperature and inlet turbulence parameters were given. At the outlet boundary the constant static pressure determined according to the outlet isentropic Mach number was prescribed.

The preliminary predictions published by Nádvorník et al. [1] were carried out for the estimated inlet free stream turbulence Tu = 2% and the viscosity ratio $\mu_t/\mu \approx 10$. Uruba et al. [14] measured turbulence characteristics using the CTA anemometer with the rotating slanted hot-wire in the inlet channel of the blade-cascade wind tunnel. Measurements were carried out in the channel axis for two unit Reynolds numbers Re = 1.3×10^6 and 5.4×10^6 with the maximal inlet Mach number $M_1 \approx 0.22$. The turbulence intensity Tu ≈ 4.8% and the viscosity ratio $\mu_t/\mu \approx 100$ were chosen at the distance x = -0.04 m from the blade leading edge for turbulence models with the turbulence viscosity defined by the relation $\mu_t = \rho k/\omega$.

The multi-block quadrilateral structured grid with a block overlapping implementation was used for the prediction by means of the in-house code. This grid allows the application of structured grids for complex geometries as well. The prediction by means of the commercial software Fluent was realised for the same computational domain with the structured grid near the blade surface combined with a non-structured triangular grid.

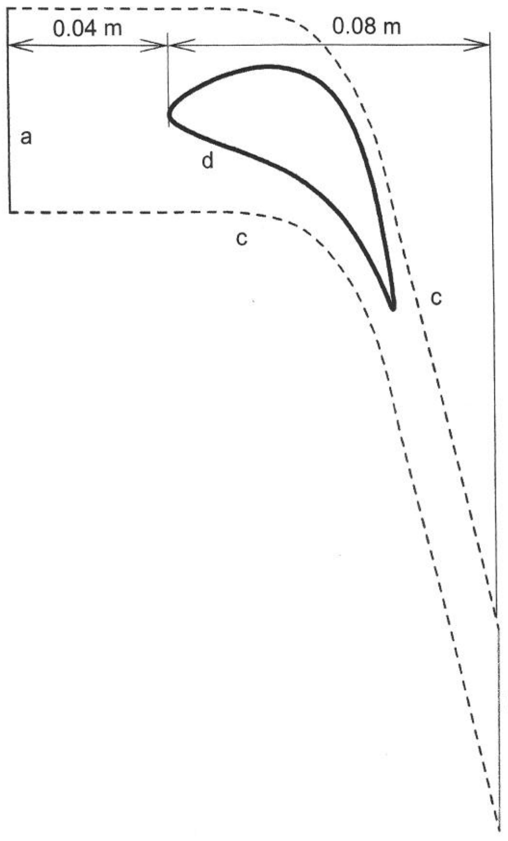


Fig.1: Scheme of the computational domain
a - inlet; b - outlet; c - symmetry; d - adiabatic wall

Numerical simulations were focused mainly on the effect of the inlet free stream turbulence and the Reynolds number on the compressible flow through the blade cascade. Calculations were realised for several Mach numbers but the majority was carried out for the isentropic Mach number $M_{2is} = 0.7$ in a wide range of the Reynolds number. The effect of the Mach number was investigated according to experimental data for the isentropic Reynolds number $Re_{2is} = 8.5\text{x}10^6$.

The velocity distribution along the blade is shown in Fig.2. The relative mean velocity is expressed by the isentropic Laval number given by the ratio of the free stream velocity and the critical velocity of sound in the form

$$\lambda = \sqrt{\frac{\kappa+1}{\kappa-1}\left[1-\left(\frac{p_w}{p_{01}}\right)^{\frac{\kappa-1}{\kappa}}\right]} \qquad (12)$$

The coordinate s is measured along the blade from the leading edge. Numerical results obtained by the EARSM model with the algebraic transition model are compared for $Re_{2is} = 8.5\times10^5$ and $M_{2is} = 0.7$ with experiments

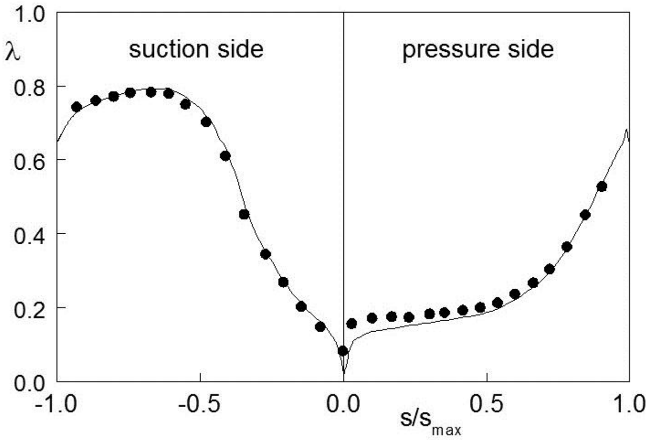
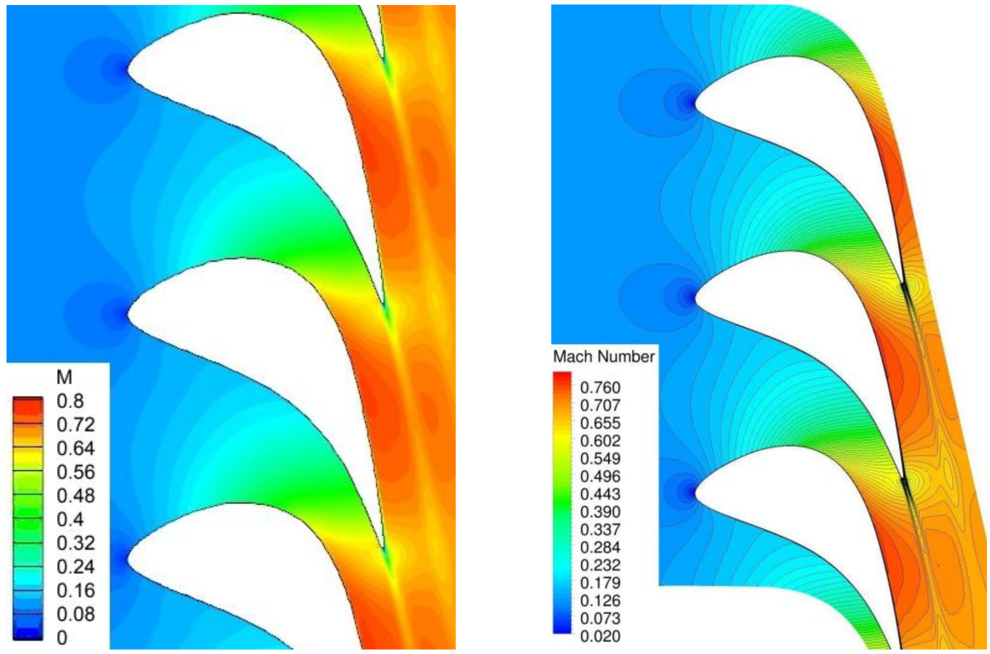


Fig.2: Distribution of mean velocity along the blade (EARSM model + algebraic transition model)

of Kladrubský [13]. For the attached flow, the velocity distribution is practically not influenced neither by the used turbulence model nor the used transition model.

Experiments of Benetka and Kladrubský [11] were carried out with the stagger angle of blades $\gamma = 41^o$, while the angle $\gamma = 41.9^o$ was used in measurements of Benetka et al. [12] and Kladrubský [13] and in numerical simulations. This change can lead to small differences between calculated and measured data.



a) EARSM model + algebraic transition model b) k-k_L-ω model

Fig.3: Field of Mach number isolines for $Re_{2is} = 8.5x10^5$ and $M_{2is} = 0.7$

The flow field is shown by means of Mach number isolines in Fig.3 for values $Re_{2is} = 8.5x10^5$, $M_{2is} = 0.7$ and inlet free stream turbulence Tu = 4.8% obtained by the EARSM model with the algebraic transition model and by the k-k_L-ω model. The agreement of both flow fields is quite good as the flow is attached.

The main aim of the numerical simulation was the comparison of calculated values of the loss coefficient ζ and the outlet angle α_2 with experimental data for two inlet free stream turbulence in a wide range of the Reynolds number Re_{2is}. These parameters were estimated in the distance 15 mm behind the outlet plane of the cascade. The loss coefficient ζ is defined as follows

$$\zeta = 1 - \left(\frac{U_2}{U_{2is}} \right)^2 \tag{13}$$

where U_2 is the mean outlet velocity and U_{2is} is the mean outlet isentropic velocity. The variation of the loss coefficient with the isentropic Mach number for the inlet free stream turbulence Tu = 4.8% is shown in Fig.4a. Numerical results obtained by the EARSM model with the transition model and by the k-k_L-ω model are compared with experimental data. The loss coefficient in the subsonic region slowly decreases with the increasing Mach number. While the EARSM model with the transition model gives a quite adequate agreement with experiments, the results obtained by the k-k_L-ω model are somewhat lower.

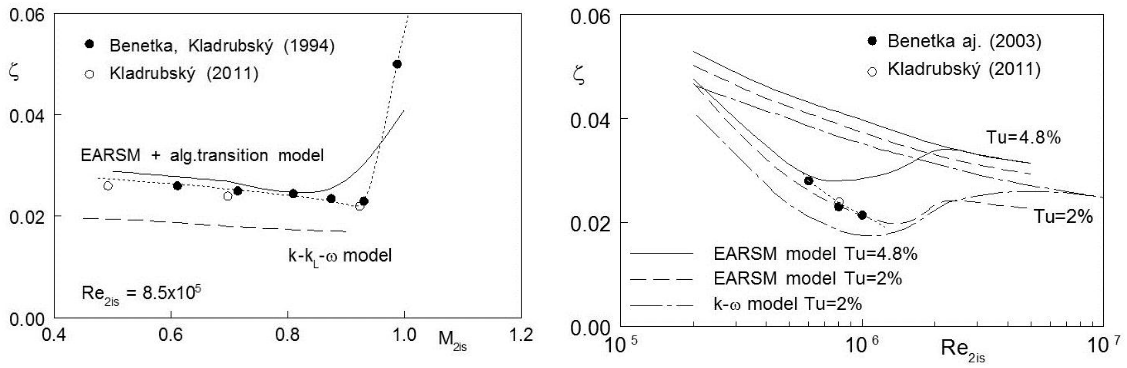


Fig.4: Variation of the loss coefficient

a) Effect of the isentropic Mach number M_{2is} b) Effect of the isentropic Reynolds number Re_{2id}

The dependence of the loss coefficient on the Reynolds number is shown in Fig.4b for the EARSM and k-ω models with the transition model. Results obtained by the EARSM model correspond acceptably to experiments. The numerical results are to a large degree dependent on inlet turbulence characteristics, i.e. on the free stream turbulence and the dissipation rate and/or on the ratio μ_t/μ respectively.

The turbulence model alone does not describe accurately the development of shear layers on blades and energy losses in the wide range of Reynolds numbers. For relatively low Reynolds numbers where the separation-induced transition can occur, the loss coefficient for the transitional flow approaches to values for fully turbulent flow. With the increasing Reynolds number, the transition onset on the suction side moves upstream and moreover the transition occurs on the pressure side as well. So the loss coefficient gradually approaches to values for the fully turbulent flow.

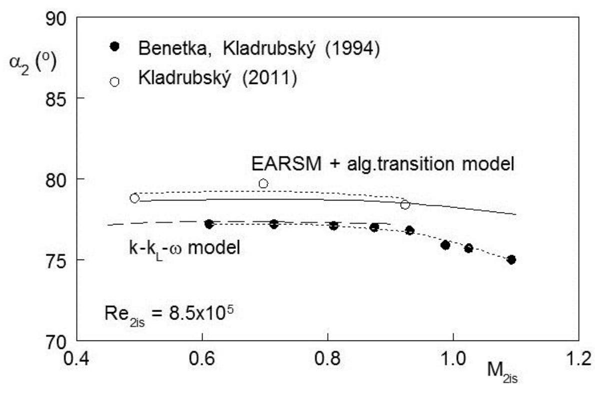


Fig.5: Variation of the outlet flow angle with the isentropic Mach number M_{2is}

The dependence of the outlet flow angle on the isentropic Mach number is shown in Fig.5. The value of the outlet flow angle is not practically influenced by the used transition model. The differences are caused by the different stagger angle.

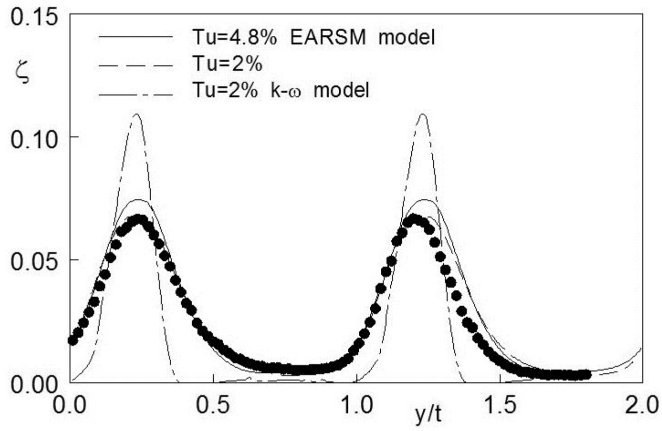


Fig.6: Distribution of the loss coefficient behind the blade cascade

The distribution of the loss coefficient behind the blade cascade is shown in Fig.6. Experimental results obtained by Kladrubský [13] at the distance x = 15 mm behind the outlet cascade plane are compared with numerical results for the algebraic transition model connected partly with the k-ω model of Kok [15] and partly with the EARSM model. The agreement of numerical simulations by the EARSM model with experimental data is quite good for both inlet free stream turbulence while the wake predicted by the two-equation k-ω model is too narrow.

Conclusion

The main aim of the contribution is the comparison of numerical results obtained by means of several turbulence and transition models with accessible experimental data for compressible subsonic flow through the turbine blade cascade at various flow conditions, especially inlet free stream turbulence Tu, the isentropic Reynolds number Re_{2is} and the isentropic Mach number M_{2is}. It follows from numerical results that it is necessary to include the bypass-transition model into the mathematical model of flow through the turbine blade cascade. The prediction can be as well influenced by the used model of turbulent heat transfer, especially at higher values of the Mach number. Nevertheless, numerical results depend not only on used turbulence and transition models but also on the used computational grid especially near the surface. The differences between various turbulence models can be seen clearly in the wake region behind blades.

Results of numerical simulations show the effect of inlet free stream turbulence on the flow through the blade cascade. This effect appears as the shift of the transition onset upstream and therefore leads to the increasing energy losses in attached flows. On the other hand, the higher inlet free stream turbulence leads to reduction of flow separation and so to reduction of energy losses.

References

[1] NÁDVORNÍK, M., STRAKA, P., PŘÍHODA, J. Numerical solution of compressible flow through a turbine cascade using various transition models, Conf. Turbostroje, Pilsen, 1/1-1/10, 2012 (in Czech)

[2] HELLSTEN, A. New two-equation turbulence model for aerodynamics applications, PhD Dissertation, Helsinki University of Technology, 2004

[3] STRAKA, P.; PŘÍHODA, J. Application of the algebraic bypass-transition model for internal and external flows, Proc. Conf. Experimental Fluid Mechanics 2010, Liberec, 636-641, 2010

[4] WALTERS, D.K.; COKLJAT, D. A three-equation eddy-viscosity model for Reynolds-averaged Navier–Stokes simulations of transitional flow, Jour. Fluids Engineering, 130, 121401/1-121401/14, 2008

[5] MENTER, F.R. Two-equation eddy-viscosity turbulence models for engineering applications, AIAA Jour., 32, 1598,-1605, 1994

[6] NARASIMHA, R. On the distribution of intermittency in the transition region of a boundary layer, Jour. Aerospace Science, 24, 711-712, 1957

[7] STRAKA, P., PŘÍHODA, J., ŠIMURDA, D. Modelling of the effect of the foregoing wake on the by-pass transition on the airfoil, Proc. Conf. Experimental Fluid Mechanics 2011, Liberec, 971-978, 2011

[8] NARASIMHA, R. The laminar-turbulent transition zone in the boundary layer, Progress in Aerospace Science, 22, 29-80, 1985

[9] SOLOMON, W.J., WALKER, G.J., GOSTELOW, J.P. The laminar-turbulent transition zone in the boundary layer, Jour. Turbomachinery, 118, 744-751, 1996

[10] MAYLE, R.E. The role of laminar-turbulent transition in gas turbine engines, Jour. Turbomachinery, 113, 509-537, 1991

[11] BENETKA, J., KLADRUBSKÝ, M. Measurement of the linear turbine blade cascade VS-33, VZLÚ Prague, Research Report 3559/94, 1994 (in Czech)

[12] BENETKA, J., ULRYCH, J., VALENTA, R. Measurement of the effect of roughness I (blade cascade VS-33 t/b = 0.7), VZLÚ Prague, Research Report V-1778/03, 2003 (in Czech)

[13] KLADRUBSKÝ, M. Measurement of linear blade cascade VS-33 along the blade height at the spacing 0.7, VZLÚ Prague, Research Report R–5166, 2011 (in Czech)

[14] URUBA, V., JONÁŠ, P., ANTOŠ, P., JELÍNEK, T., MICHÁLEK, J. Turbulence study of SKODA turbine cascade in VZLÚ wind tunnel, Proc. Conf. Turbostroje, Pilsen, 3/1-3/8, 2012 (in Czech)

[15] KOK, J.C. Resolving the dependence on free stream values for the k-ω turbulence model, AIAA Jour., 38, 1292-1295, 2000

Acknowledgement
The work was supported by the institutional support RVO 61388998 and by the Czech Science Foundation under grants P101/10/1329 and P101/12/1271.

Ing. NÁDVORNÍK Michal, Doosan Škoda Power Ltd., Tylova 1/57, 301 28 Pilsen, Czech Republic, +420 378185553, michal.nadvornik@doosan.com
Ing. STRAKA Petr PhD., VZLÚ Aerospace Research and Test Establishment, Beranových 130, 199 05 Prague 9, Czech Republic, +420 266310578, straka@vzlu.cz
Prof. Ing. PŘÍHODA Jaromír CSc., Institute of Thermomechanics AS CR, v.v.i., Dolejškova 5, 182 00 Prague 8, Czech Republic, +420 266053824, prihoda@it.cas.cz