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Simulation of Transonic Flow through a Mid-span Turbine Blade Cascade for Various Mach Numbers

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Abstract. The contribution deals with the numerical simulation of 2D transonic flow through a mid-span turbine blade cascade for several Mach numbers by means of the EARSM turbulence model of Hellsten [1] connected with the algebraic bypass transition model of Straka and Příhoda [2]. Both models are implemented into an in-house numerical code based on the finite volume method. The γ transition model of Menter et al. [3] with SST turbulence model accessible in the commercial code ANSYS Fluent was used for the comparison.

INTRODUCTION

Transonic flow through blade cascades is connected with the interaction of the shock wave and the boundary layer on the blade surface. This interaction substantially affects the flow field in the blade cascade. In case of the laminar boundary layer, the shock-wave/boundary-layer interaction is usually accompanying with the flow separation followed by the transition in separated flow. Existing empirical correlations for modelling of the separation-induced transition are based on experimental data concerned subsonic flows around aerofoils with the separation caused by the adverse pressure gradient only (so-called separation bubble). The application of these correlations to transonic flows where the separation is caused by the shock-wave interaction with boundary layer gives usually a shorter separation length (see Straka et al. [4] or Váchová et al. [5]). The present contribution deals with the effect of the Mach number on the modelling of the separation-induced transition due to the shock-wave/boundary-layer interaction.

MATHEMATICAL MODELS

The numerical simulation of compressible flows is based on the solution of the conditionally-averaged Navier-Stokes equations completed by the constitutional relations and by a turbulence model, a model of turbulent heat transfer and by a model of the laminar/turbulent transition. The basic mathematical model consists of the explicit algebraic model of Reynolds stresses (EARSM) by Hellsten [1], the algebraic transition model proposed by Straka and Příhoda [2] and the turbulent heat transfer model based on the generalized gradient hypothesis according to Launder [6].

The EARSM turbulence model is used in the form corresponding to models with the turbulent viscosity. Turbulent scales are expressed by the turbulent energy k and by the specific dissipation rate ω by means of the SST turbulence model of Menter [7]. Turbulent time scale $\tau \sim 1/\omega$ near the wall is given by the Kolmogorov viscous time scale. The production term in the turbulent energy equation is modified for the reduction of the undesirable overproduction of the turbulent energy in the stagnation region. Production and destruction terms in the equation for

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the turbulent energy are multiplied by the intermittency coefficient γ. Similarly, the effective viscosity is given by $\mu_{ef} = \mu + \gamma\mu_t$ in the transition region. The turbulent heat flux ix expressed by the relation

$$q_i = -C_t \frac{\tau_{ij}}{\omega} \frac{\partial \overline{T}}{\partial x_j} \tag{1}$$

with constant C_t = 0.3. The 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 γ_i is described by the relation

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

according to Narasimha [8]. The transition onset is given by the empirical correlation for the momentum Reynolds number $Re_{\theta t}$ = f (Tu, λ_t) where Tu (%) is the free-stream turbulence level and λ_t is the pressure-gradient parameter. The transition length is expressed using the parameter $N = \hat{n}\sigma\, Re_{\theta t}^3$ where $\hat{n}$ is the spot generation rate and σ is the spot propagation rate introduced by Narasimha [8]. The parameter N for the attached flow is similarly correlated by the empirical relation in the form N = g (Tu, λ_t) proposed by Solomon et al. [9]. The onset of transition in separated flow is given by the correlation according to Mayle [10] in the form

$$Re_{xt} = 300\, Re_{\theta s}^{0.7} + Re_{xs} \tag{3}$$

where $Re_{\theta s}$ is the momentum Reynolds number at the separation and Re_{xs} is the Reynolds number related to the distance of the separation from the leading edge. The transition length of the separation is given according to Walker [11] by the relation

$$\hat{n}\sigma = \frac{Re_{xt}^{-1.34}}{40} \tag{4}$$

and so the same approach can be applied as in the attached flow.

For prediction of transitional flows in complex geometries, the application of local variables is necessary. The momentum Reynolds number is replaced according to Langtry and Menter [12] by the maximum of the vorticity Reynolds number in the form

$$Re_{\Omega} = y^2 \left|\Omega\right| / \nu \tag{5}$$

where y is the distance from the wall and Ω is the absolute value of the vorticity tensor. The link between both Reynolds numbers is expressed by the relation $Re_\theta = Re_{\Omega max} / C$ where the parameter C depends on the pressure gradient. The variation of the parameter C with the pressure gradient parameter was estimated by means of similar solutions of Falkner-Skan velocity profiles. The mathematical model was implemented into the in-house numerical code based on the finite volume method. The multi-block quadrilateral structured grid with a block overlapping implementation refined near walls was applied for numerical simulations.

The γ transition model of Menter et al. [3] is a one-equation local-correlation transition model based on the equation for the intermittency coefficient. This simplified version of the γ-Re_θ transition model of Langtry and Menter [12] is based on the transport equation

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial\left(\rho U_j \gamma\right)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right] \tag{6}$$

with the production term

$$P_\gamma = F_{length}\rho S \gamma (1-\gamma) F_{onset} \tag{7}$$

where S is the absolute value of strain rate and F_{onset} and F_{length} are threshold functions given by empirical correlations for the onset and length of transition region.
The destruction term

$$E_\gamma = c_{a2}\rho\Omega\gamma F_{turb}\left(c_{e2}\gamma - 1\right) \tag{8}$$

allows to model the relaminarization of the boundary layer. All empirical correlations are based on local variables only. The transition model is connected with the SST turbulence model.

RESULTS

The both transition models were used for the simulation of 2D transonic flow through the linear turbine blade cascade TR-Z-1 at various Mach numbers M_{2is}. The scheme of the turbine blade cascade is shown in Fig. 1. Predictions were carried out for the relative spacing t/c = 0.718, inlet angle α_1 = 29.1° and for isentropic Mach number M_{2is} in the range from 1.091 up to 1.515. The outlet isentropic Mach number M_{2is} corresponds to the static pressure p_2 determined by the data reduction method in the traversing plane behind the blade cascade. Numerical simulations were compared with experimental data of Luxa et al. [13]. The data reduction method proposed by Amecke and Šafařík [14] was used for the evaluation of experimental data and numerical results as well.

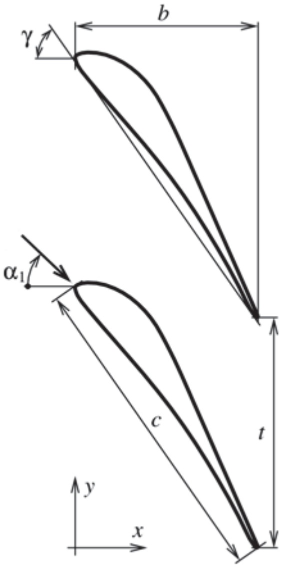
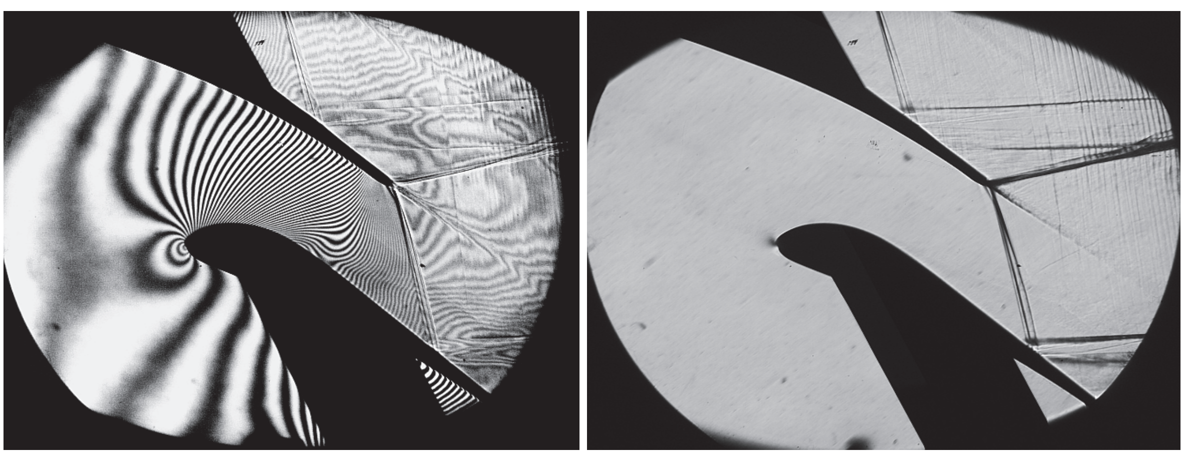


FIGURE 1. Scheme of the blade cascade

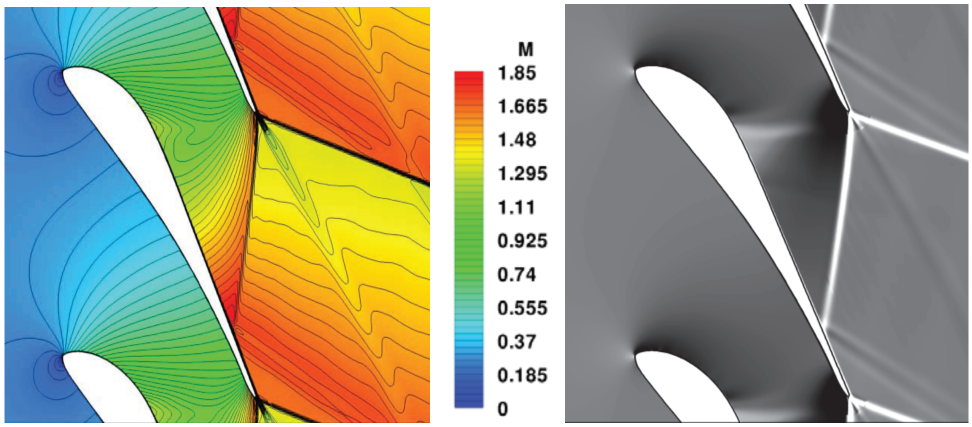
The inlet of the computational domain was in the distance of 0.55c from the blade leading edge and the outlet in the distance 0.7c behind trailing edges. The outlet part of the computation domain used in the ANSYS Fluent code was extended up to 6c to reduce the effect of the shock-waves reflection from the domain outlet. Inlet boundary conditions are prescribed by the constant total pressure, total temperature and inlet flow angle. The outlet boundary condition is given by the constant static pressure determined according to the outlet isentropic Mach number. Periodicity conditions were applied on side boundaries of computation domains. The inlet free-stream turbulence parameters corresponding to turbulence intensity Tu = 1.5% and the ratio of the turbulent and molecular viscosity μ_t/μ = 50 are used. Predictions were focused on the effect of the Mach number on the transition modelling in the separated flow caused by the shock-wave/boundary-layer interaction. Numerical results are presented mainly for the Mach number M_{2is} = 1.515 and compared with other results particularly for M_{2is} = 1.205 (see Straka et al. [4]).



a) Interferometric picture b) Schlieren picture

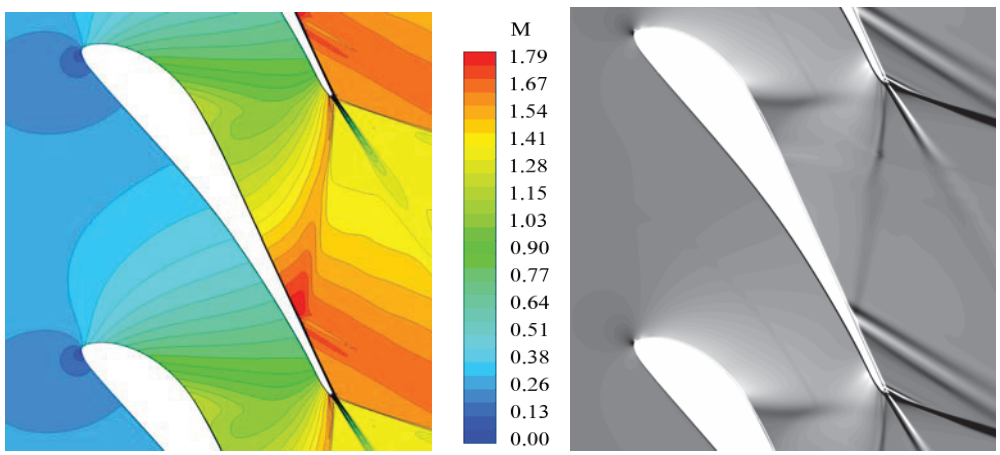
FIGURE 2. Interferometric and schlieren pictures for the Mach number M_{2is} = 1.515

Interferometric and schlieren pictures obtained for M_{2is} = 1.515 are shown in Fig. 2. The interaction of the inner branch of the exit shock wave with the boundary layer on the suction side is connected with the separation on the laminar boundary layer. The Mach number isolines and the numerical schlieren picture of the flow field obtained by the algebraic transition model are shown in Fig. 3. Similarly numerical results obtained by the γ transition model of Menter et al. [3] are presented in Fig. 4. As it can be seen, the both transition models give very similar results. The agreement of the predicted flow field structure with experimental results is good. The separation zone around the location of the shock-wave impact is clearly apparent in experimental and numerical results.



a) Mach number isolines b) Numerical schlieren picture

FIGURE 3. Flow field in the blade cascade for M_{2is} = 1.515 (algebraic transition model)



a) Mach number isolines b) Numerical schlieren picture

FIGURE 4. Flow field in the blade cascade for M_{2is} = 1.515 (γ transition model)

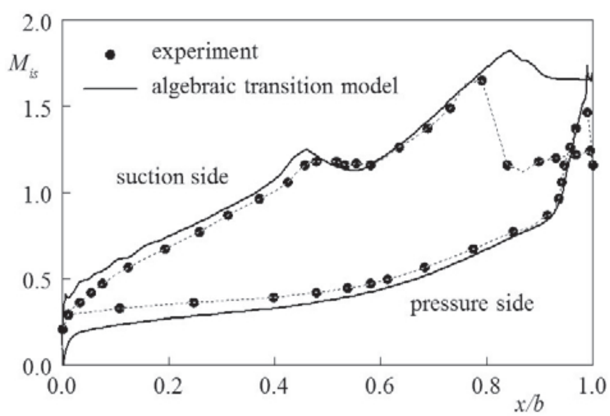


FIGURE 5. Distribution of the isentropic Mach number along the blade for M_{2is} = 1.515

The distribution of the isentropic Mach number along the blade surface for M_{2is} = 1.515 predicted by the algebraic transition model is compared with experimental data in Fig. 5. The γ transition model of Menter et al. [3] gives practically the same results. The agreement with experimental data is acceptable but the predicted position of the shock-wave impact is shifted to the trailing edge.

The skin friction distribution along the blade surface for M_{2is} = 1.515 is presented in Fig. 6. The skin friction coefficient is defined by the relation $C_f = \tau_w/(p_{01}-p_1)$. The both transition models give similar results particularly on the pressure side where a very short separation can be seen tightly before the trailing edge. The sudden change of the surface curvature of the suction side at the distance $x/b \approx 0.55$ leads to some changes in the Mach number distribution (see Fig. 5) and to a short laminar separation bubble. This tendency obtained by both transition models can be seen in the skin friction distribution in Fig. 6.

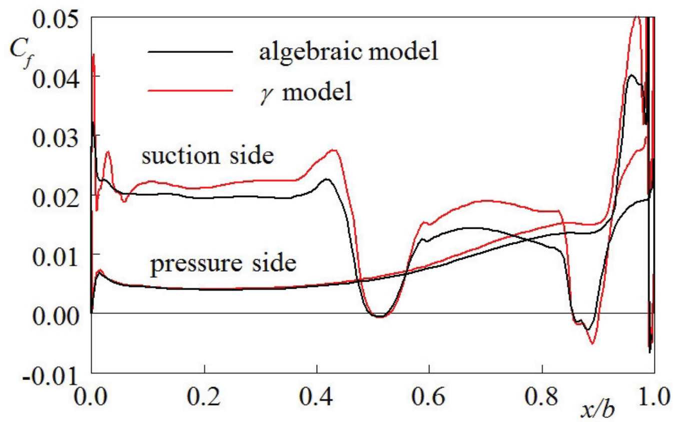
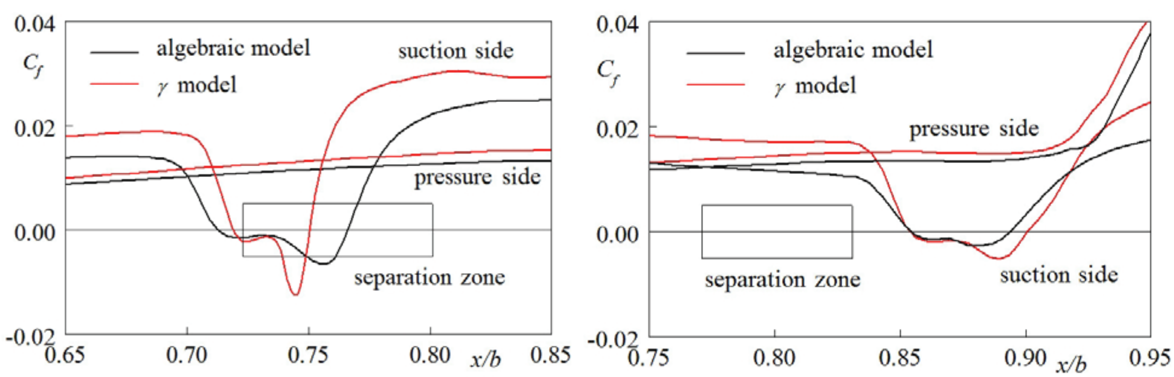


FIGURE 6. Skin friction distribution for M_{2is} = 1.515

The flow field in the blade cascade is further influences by the interaction of the exit shock wave with the laminar boundary layer on the suction side of the blade connected with flow separation and subsequently to the laminar-turbulent transition and to the reattachment. The impact of the shock wave on the suction side is located for M_{2is} = 1.205 at the distance $x/b \approx 0.770$ from the leading edge and moves with the increasing Mach number towards the trailing edge. The location of the shock-wave impact for M_{2is} = 1.515 can be estimate from the interferometric picture (see Fig. 2) about $x/b \approx 0.807$.



a) M_{2is} = 1.205 b) M_{2is} = 1.515

FIGURE 7. Detail of the skin friction distribution

The detail of skin friction distribution with separation zones for Mach numbers M_{2is} = 1.205 and 1.515 is given in Fig. 7. The separation zone estimated from experimental results is marked by the rectangle. The extent of separation is approximately from $x/b \approx 0.723$ to 0.801 for M_{2is} = 1.205. Both transition models give a rather short separation zone.

The separation zone takes the part of the blade from $x/b \approx 0.771$ to $x/b \approx 0.831$ for M_{2is} = 1.515 (see Fig. 7b). The length of the separation is shorter with the increasing Mach number and is rather shifted to the trailing edge as the impact of the shock wave on the blade moves downstream with the increasing Mach number. In a similar way the predicted separation zone is shifted to the trailing edge with the increasing Mach number but this shift is somewhat greater. The dependence of the separation zone location on the Mach number M_{2is} is shown in Fig. 8. Various trends towards the shift of the separation location for experimental and numerical results are obvious from this figure.

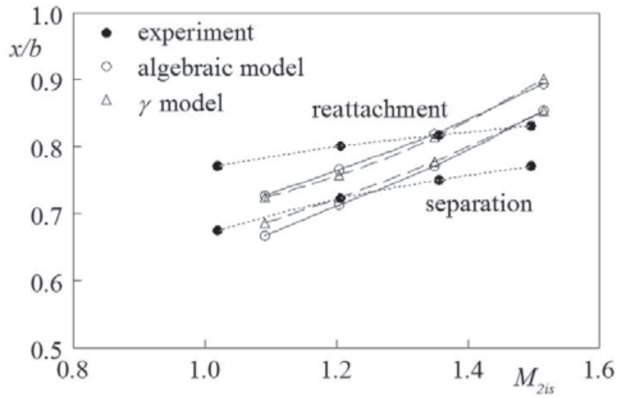


FIGURE 8. Variation of the separation zone location with the Mach number M_{2is}

One of possible causes of this difference can be the way of the prescription of outlet boundary condition for numerical simulations. The prescribed outlet static pressure p_2 was estimated by the data reduction method in the traversing plane behind the blade cascade and was used for the estimation of the outlet isentropic Mach number M_{2is}. The static pressure in the settling chamber behind the test section is measured during experiments with the equivalent isentropic Mach number M_{2isSC}. The variation of the Mach number M_{2is} in the traversing plane with the Mach number M_{2isSC} is presented in Fig. 9. The difference between both Mach numbers decreases with the increasing Mach number in the settling chamber M_{2isSC}.

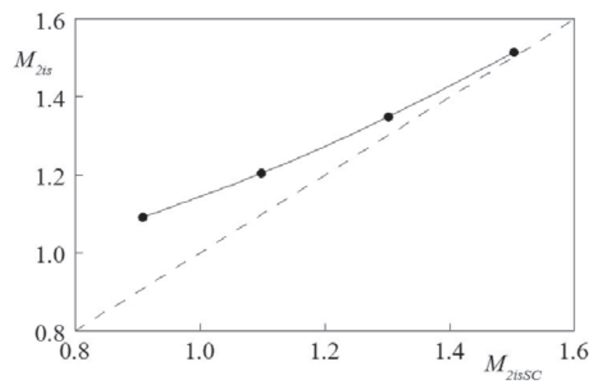


FIGURE 9. Variation of the Mach number M_{2is} with the Mach number M_{2isSC}

A better agreement may be obtained by the numerical simulations using the computational domain corresponding to the experimental arrangement i.e. including the settling chamber. Numerical simulations predict a shorter separation zone with the increasing Mach number in conformity with experiments. Nevertheless, empirical correlations for the transition length should be corrected for the effect of the Mach number, as all existing correlations for the separation-induced transition were derived for subsonic flows around aerofoils where the separation is caused by the adverse pressure gradient.

CONCLUSIONS

Numerical simulations of 2D transonic flow through the linear mid-span turbine blade cascade were carried out for outlet isentropic Mach numbers M_{2is} in the range from 1.091 up to 1.515 and compared with experimental data. The algebraic transition model of Straka and Příhoda [2] and γ transition model of Menter et al. [3] were used for predictions. Simulations were focused on the effect of the Mach number on the modelling of the separation-induced transition due to the shock-wave/boundary-layer interaction.

Both transition models give very similar results. The predicted flow structure with two reflected shock waves and the expansion region between them corresponds well to experimental results but the separation length is shorter with the increasing Mach number and is rather shifted to the trailing edge as the impact of the shock wave on the blade moves downstream with the increasing Mach number.

This difference between measured and predicted position of the shock-wave impact should be caused by the prescription of the outlet boundary condition. A better agreement should be achieved by the application of the computational domain corresponding to the experimental arrangement. Afterwards it should possible to prove existing correlations for the separation-induced transition for the effect of the Mach number.

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REFERENCES

1. A. Hellsten, "*New two-equation turbulence model for aerodynamics applications*", Ph.D. thesis, Helsinki University of Technology, 2004.
2. P. Straka and J. Příhoda, "Numerical simulation of compressible flow through high-loaded turbine blade cascade", in *Proc. Conf. Topical Problems of Fluid Mechanics*, Praha, pp. 131-134, 2014.
3. F. R. Menter, P.E. Smirnov, T. Liu and R. Avancha, "A one-equation local correlation-based transition model", *Flow, Turbulence and Combustion*, **95**, pp. 583-619, 2015.
4. P. Straka, J. Příhoda and D. Fenderl, "Simulation of transonic flow through a mid-span turbine blade cascade with the separation-induced transition", in *Proc. Conference Topical Problems of Fluid Mechanics*, Praha, pp. 267-274, 2017.
5. J. Váchová, M. Luxa, J. Příhoda and D. Šimurda, "Transition model application on mid-section turbine blade cascade", in *Proc. 12th ISAIF Symposium*, Lerici, Paper No. ISAIF12-100, 2015.
6. B. E. Launder, "On the computation of convective heat transfer in complex turbulent flows", *Jour. Heat Transfer*, **110**, pp. 1112-1128, 1988.
7. F. R. Menter, "Two-equation eddy-viscosity turbulence models for engineering applications", *AIAA Jour.*, **32**, pp. 1598-1605, 1994.
8. R. Narasimha, "The laminar-turbulent transition zone in the boundary layer", *Prog. Aerosp. Sci.*, **22**, pp. 29-80, 1985.
9. W. J. Solomon, G. J. Walker and J. P. Gostelow, "The laminar-turbulent transition zone in the boundary layer", *Jour. Turbomachinery*, **118**, pp. 744-751, 1996.
10. R. E. Mayle, "The role of laminar-turbulent transition in gas turbine engines", *Jour. Turbomachinery*, **113**, pp. 509-537, 1991.
11. G. J. Walker, "Transitional flow on axial turbomachine blading", *AIAA Jour.*, **27**, pp. 595-607, 1989.
12. R. B. Langtry and F. R. Menter, "Correlation-based transition modeling for unstructured parallelized computational fluid dynamics codes", *AIAA Jour.*, **47**, pp. 2894-2906, 2009.
13. M. Luxa, D. Šimurda, P. Šafařík, J. Synáč and B. Rudas, "High-speed aerodynamic investigation of the mid-section of 48" rotor blade for the last stage of steam turbine", in *Proc. 10th European Conference on Turbomachinery, Fluid Dynamics and Thermo-Dynamics,* Lappeenranta, pp. 360-369, 2013.
14. J. Amecke and P. Šafařík, "*Data reduction of wake flow measurements with injection of another gas*", DLR-Forschungsbericht 95-32, Göttingen, 1995.