National Conference with International Participation

ENGINEERING MECHANICS 2008

Svratka, Czech Republic, May 12 – 15, 2008

LOSSES IN TURBINE STAGES WITH INCREASED SURFACE ROUGHNESS OF BLADES

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Summary: *The influence of surface roughness in energetic losses on a turbine blade cascade is presented here. The impact of Reynolds and Mach number by the different surface roughness on losses is described. Results from experimental steam turbine are compared with information received after investigation on a linear blade cascade in an aerodynamic wind tunnel.*

1. Introduction

Losses in a turbine stage depend on many geometrical and flow parameters. Profile losses are connected with a formation of boundary layer on flow round blade surfaces. The character of boundary layer is given by Reynolds number. Many characteristic flow effects start by certain valve of Mach and Reynolds number. We can observe the flow separation and again the sticking of the boundary layer to the surface. There is also proved the relation between the surface roughness and the skin friction coefficient. That means the surface roughness influences the formation of the boundary layer and in this way the profile losses. The common knowledge about the surface roughness influence on the magnitude of the skin friction coefficient are completely elaborative for the simply defined objects for example for the plane desk and the pipeline. By the evaluation of the surface roughness influence on the profile losses of turbine blades and whole stages that is necessary to use the analogy with the plane desk or to use results from experiments on blade profile grids. Very important are all measurements of turbine stage efficiency with the various magnitude of surface roughness and Reynolds number. There is different literature on this subject (Hummel, F., Lötzerich M. Cardamone, P. & Fottner, L., 2005; Baynton, J. L., Tabibzadeh, R., Hudson, S. T.; Bans, J. P., Taylor, R. P., McClain S. T. & Rivir, R. B., 2001), on airfoils (Von Rooij R. P. J. O. M. & Timmer W. A., 2003), and an endeavor to predict the effects of surface roughness on turbine stage efficiency with the help of computation (Jůza Z. & Tajč, L. 2006; Mellray, H. M., Budnik, R. S. & McEliget D. M., 2003). The main aim of this work is to compare the results from tests on aerodynamic wind tunnel with experimental investigations on a steam turbine.

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The same blade profiles were used by both types of experiments and by prediction of losses with the help of computation.

2. Surface roughness effects on profile losses

The common knowledge about the surface roughness influence on the formation of boundary layer by the plane desk it's possible to applicate that by turbine blade profiles. Just the plane desk appears as a suitable example for the theoretical analysis of all features connected with the existence of boundary layer and the influence of surface roughness on increasing of energetic and pressure loss.

With the inputs equation and the momentum loss there is possible to derive the integral formula for the boundary layer:

$$\frac{d\delta^{**}}{dx} + \frac{u_0^{'}\delta^{**}}{u_0}\left(2 + H + M_0^2\right) = \frac{\tau_0}{\rho_0 u_0^2}, \tag{1}$$

where $H = \frac{\delta^*}{\delta^{**}}$ is the relation of the mass flow and the impulse boundary layer

$M_0 = \frac{u_0}{a_0}$ Mach number

$c_f = \frac{\tau_0}{\rho_0 u_0^2}$ local skin friction coefficient

C_f is possible to express as a function of non-dimensional parameters

$$C_f = \varphi\left(\mathrm{Re}^{**}, M, \frac{u_0^{'}\delta^{**}}{u_0}, \frac{u_0^{''}\delta^{**}}{u_0}, \ldots\right), \tag{2}$$

where $\mathrm{Re}^{**} = \frac{u_2\delta^*}{\upsilon}$

Impulse thickness of boundary layer depends on Reynolds number. C_f can be for simple geometrical formations and flow parameters theoretically elaborated. In common praxis there are more important experimentally proved data. Skin friction coefficient for desk of length L is presented in Fig. 1.

For every surface roughness there is an area where the boundary layer doesn't depend on Reynolds number. k_s is the sand grain roughness height. Roughness is mainly expressed by centerline average roughness Ra where $k_s = 6{,}4$ Ra.

Similar features must exist for every blade cascade and whole turbine stages. The factual magnitude of transient Reynolds number and loss coefficient mast exist for every surface roughness and real sizes of blades. There can be find by computation or experiments.

In practice is very important to define pressure losses. For example the pressure loss in a pipeline length L and diameter D is given by $\Delta p = \lambda \frac{\rho C_0^2}{2} \cdot \frac{L}{D}$, where the friction coefficient $\lambda = 8 \cdot C_f$.

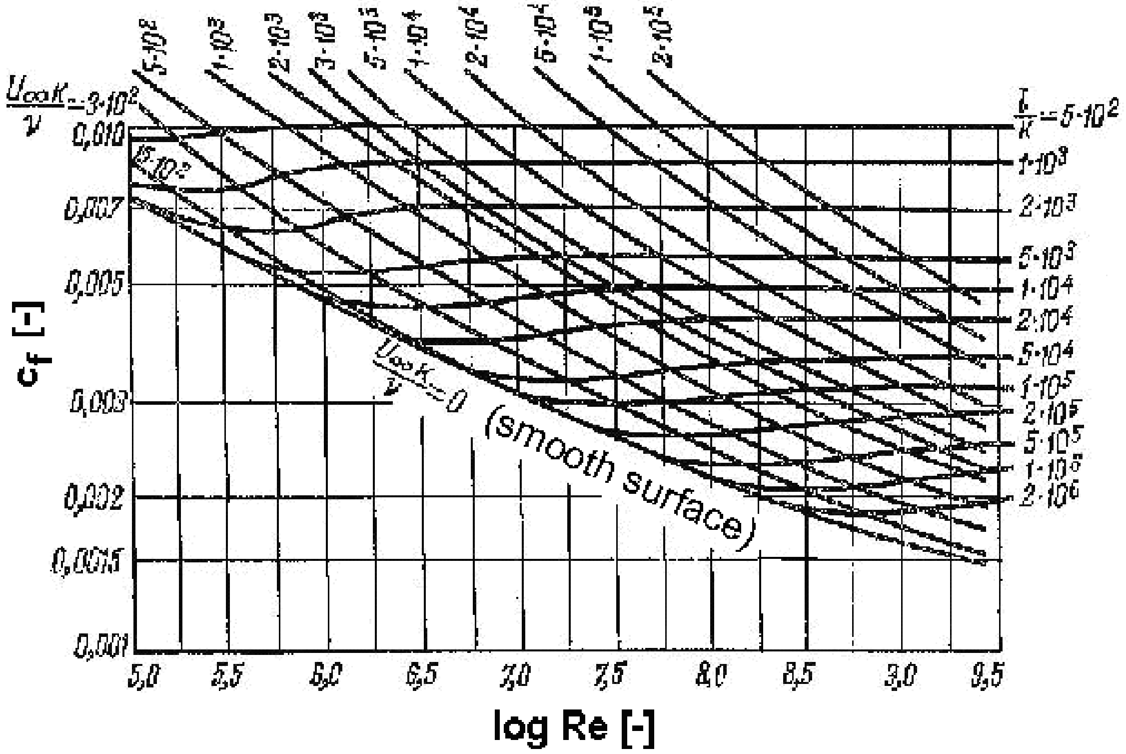

Fig. 1: Skin friction coefficient for a plane desk

The pressure loss of blade cascade by incompressible flow can be find from formula

$$\Delta p = \zeta \frac{1}{2} \rho c_0^2 ,$$

Since a blade channel is similar to a tube, the loss coefficient ζ will be reciprocally proportion to the pitch to chord ratio t/b. Experiment from aerodynamic wind tunnel with a cascade of constant length only confirms it – see Fig. 2.

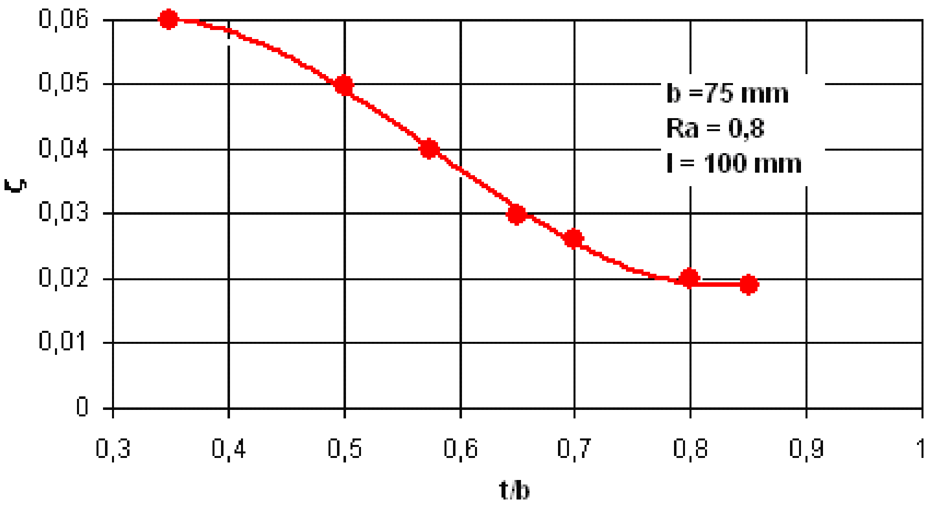

Fig. 2: Profile losses of blade cascade

3. Losses in a blade cascade with a roughened surface

A series of loss coefficient measurement was performed for the cascade with an artificially increased surface roughness (Benetka, J., Ulrich, J. & Valenta, R., 2003). By the cascade with vanes for the HP parts of steam turbines was implicated the pitch to chord ratio t/b = 0.7, Reynolds number was changed in the range Re = (6 ÷ 10) · 10^5, Mach number was chosen in the range M_{2is} = 0,4 ÷ 1,2. The surface roughness was adapted by gluing different grains carborundum powder on a basic surface. The results from investigation on an aerodynamic wind tunnel are shown on Fig. 3.

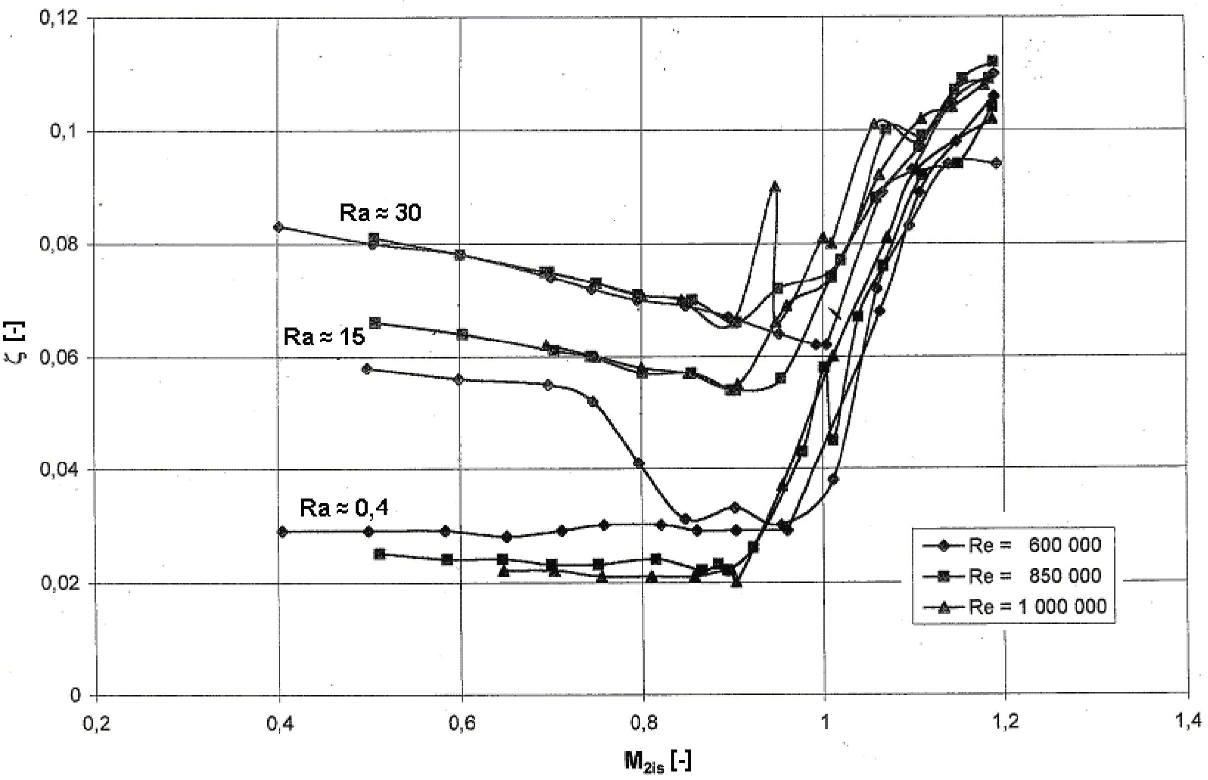

Fig. 3: Surface roughness influence on profile losses.

The influence of Reynolds and Mach number on profile losses is quite evident. The effect of surface roughness in transonic flow isn't so visible.

The exit angle of the flow from the blade cascade depends also on the surface roughness and Mach number. The results from experiments are put down on Fig. 4.

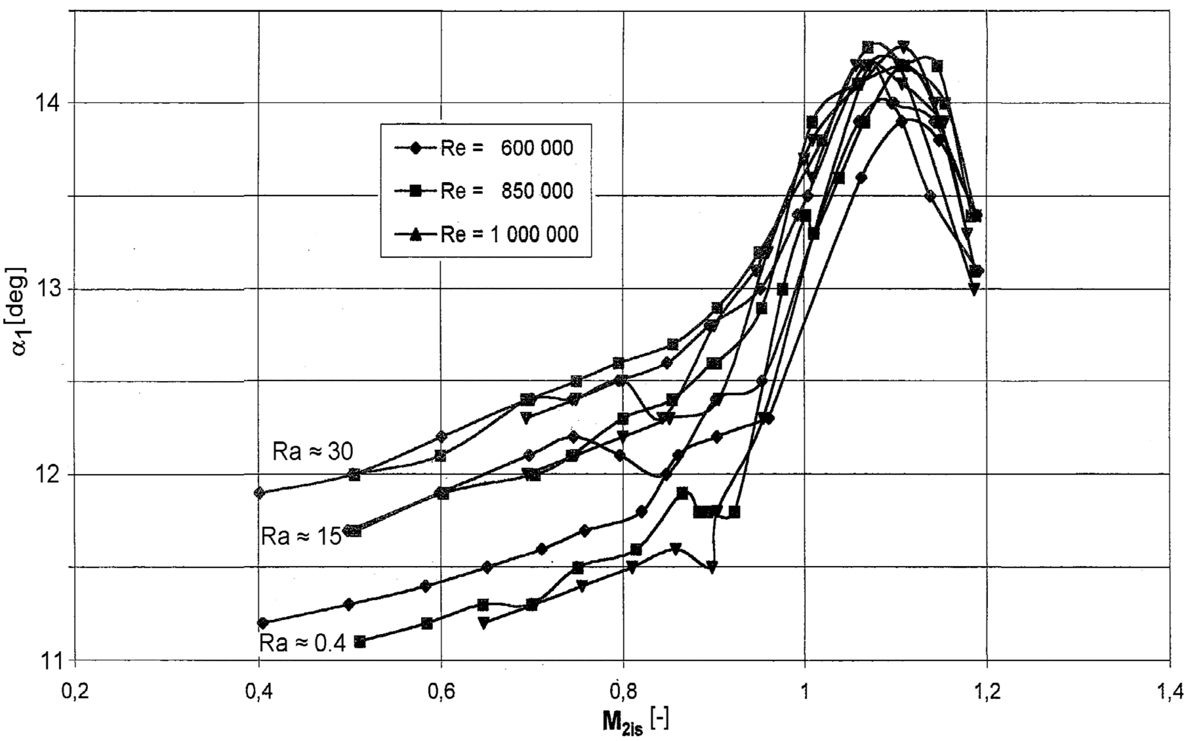

Fig. 4: Surface roughness influence on exit angle α_1

There was endeavor to find which part of blade profile with its surface roughness more or less effects on the result value of losses. The influence of partially roughned blade was investigated by means of standard HP stationary blade. The results are summarized in Fig. 5.

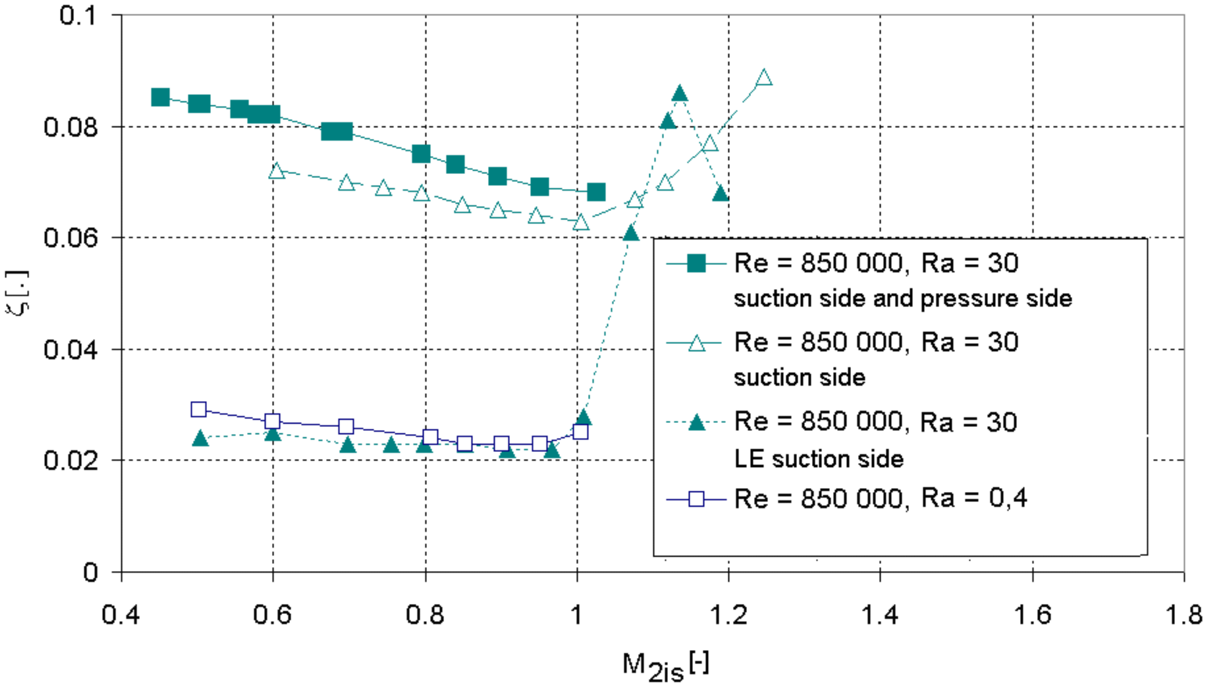

Fig. 5: Sand – roughness effect – partially roughened surface of vanes

The first modification compared with the smooth surface was that one with roughened strip along the LE on suction side. While the inlet angle and Reynolds number were kept constant ($\alpha_1 = 0$ deg, Re = 8.5 * 105), the outlet Mach number was gradually increased from the value of 0.5 to 1.2. According to Fig. 5 there is no measurable difference between the original (Ra ≈ 0.4) and modified (20 mm strip, Ra ≈ 30)) module up to $M_{2is} = 1$. Quantitatively remarkable increase of ζ occurs in subsonic region (predominant friction loss) when the whole suction side is characterized by Ra ≈ 30. Subsequent decrease of pressure side quality led to relatively small increase of ζ. This effect can be explained by considerably lower velocity of the flow along the pressure side.

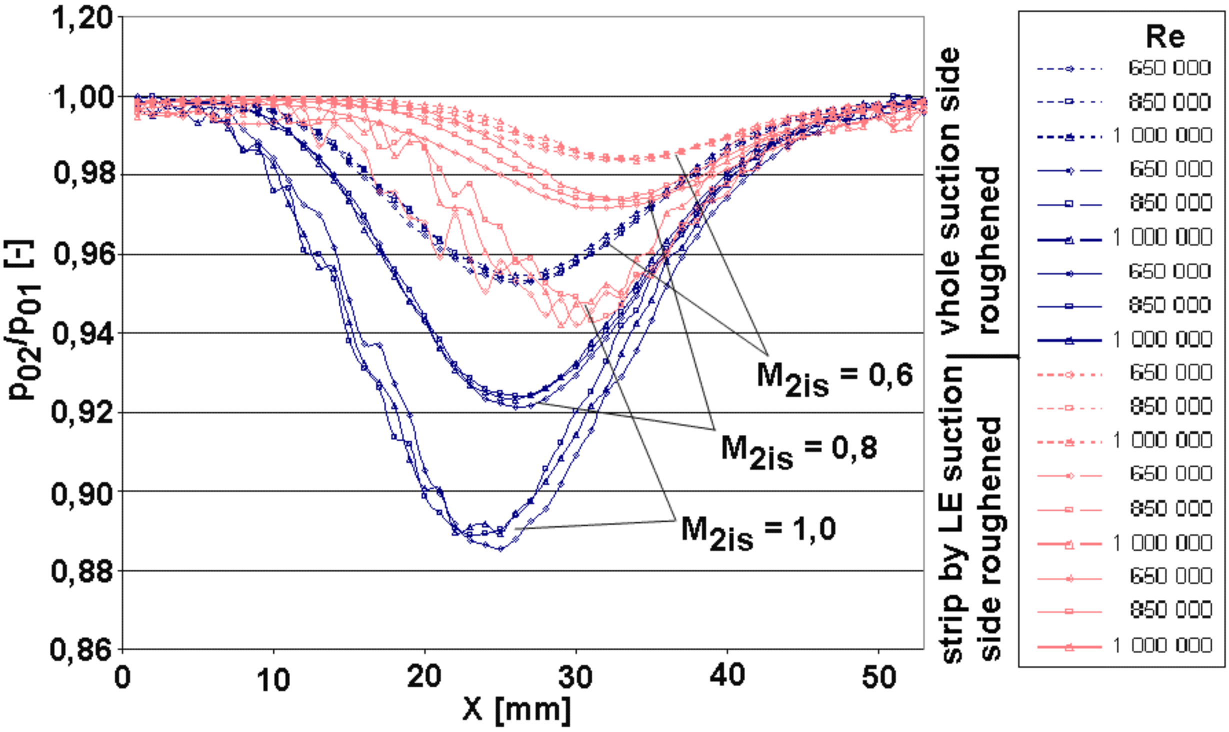

Fig. 6: Total pressure losses in wake.

Total pressure losses in a wake for three Mach numbers M_{2is} (0.6; 0.8 a 1.0) and three Reynolds numbers (6.5 * 10^5, 8.5 * 10^5 and 1 * 10^6) are depicted in Fig. 6. Differences of losses in a wake between the partially roughened suction side and the whole roughened suction side are quite evident. The impact of Reynolds number on losses isn't in this case two significant.

4. Computational study of surface roughness impact on losses in a blade cascade

The computational study was carried out with the help of commercial program FLUENT. The same blade grid tested on an aerodynamic wind tunnel was used by computations. Also the working medium was air. The basic geometry of blade grid is shown in Fig. 7.

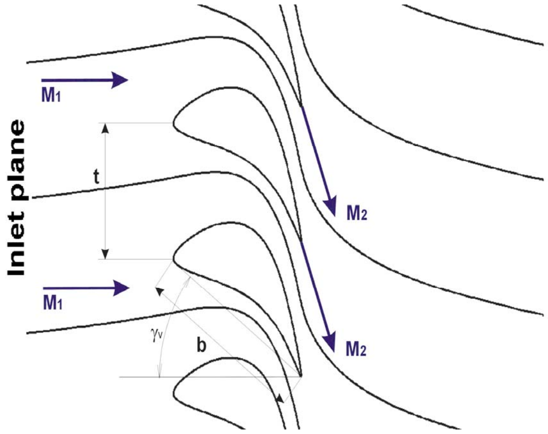

Fig. 7: Basic geometry of blade grid

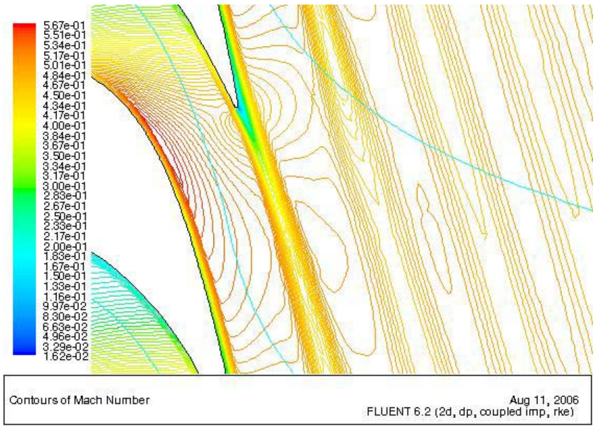

Fig. 8: Mach number distribution

$M_{2is} = 0{,}5$; $k_s = 40$

Mach number was changed in the range $M_2 \approx (0.5 \div 1.3)$ and the surface roughness was chosen $k_s = 3.2$; 12 a 40 μm. The characteristic Mach number distribution for $M_{2is} = 0.5$ and $k_s = 40$ is presented in Fig. 8.

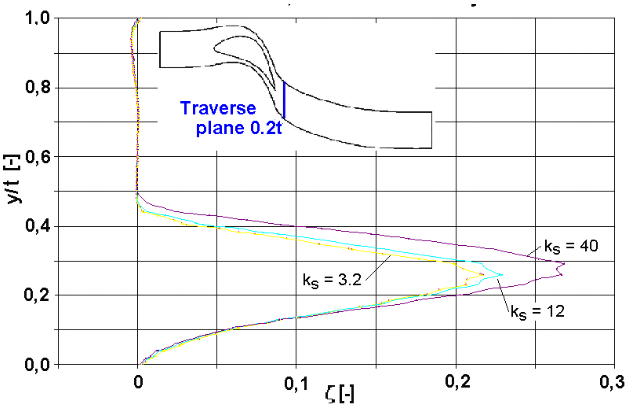

Fig. 9: Distribution of losses

for $M_{2is} = 0{,}5$

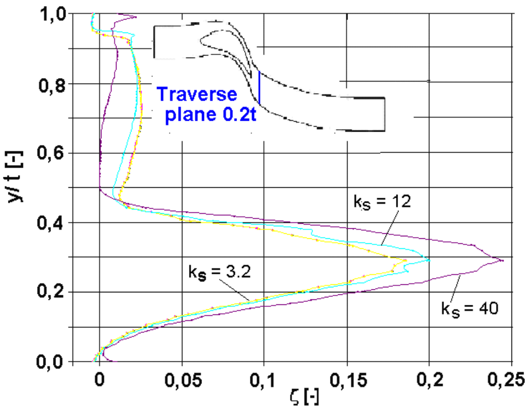

Fig. 10: Distribution of losses

for $M_{2is} = 1{,}07$

The increase roughness effects on the thickness of the boundary layer on the profile suction side. The loss coefficient distribution over the pith on Fig. 9 only confirms it. The increase of losses downstream of the threading edges appears only in a wake. By the transonic flow as it is shown in Fig. 10 the effect of increased roughness appears on the section side and also on the profile pressure side. In the part out of the wake the losses are even decreasing.

The presented results are acceptable only in the traverse plane 0.2t downstream of the thrilling edges. The dependence of the loss coefficient on the distance from the blade cascade is presented on Fig. 11. The effect of the roughened surface by the subsonic flow is very good proved. The losses are in this case constant. By the transonic flow the losses are with the increasing distance also increasing. The higher Mach number the higher distance is necessary for the stabilization of losses. The effect of roughness on losses isn't by the transonic flow essential. The tested profile isn't designed for the application by the transonic flow.

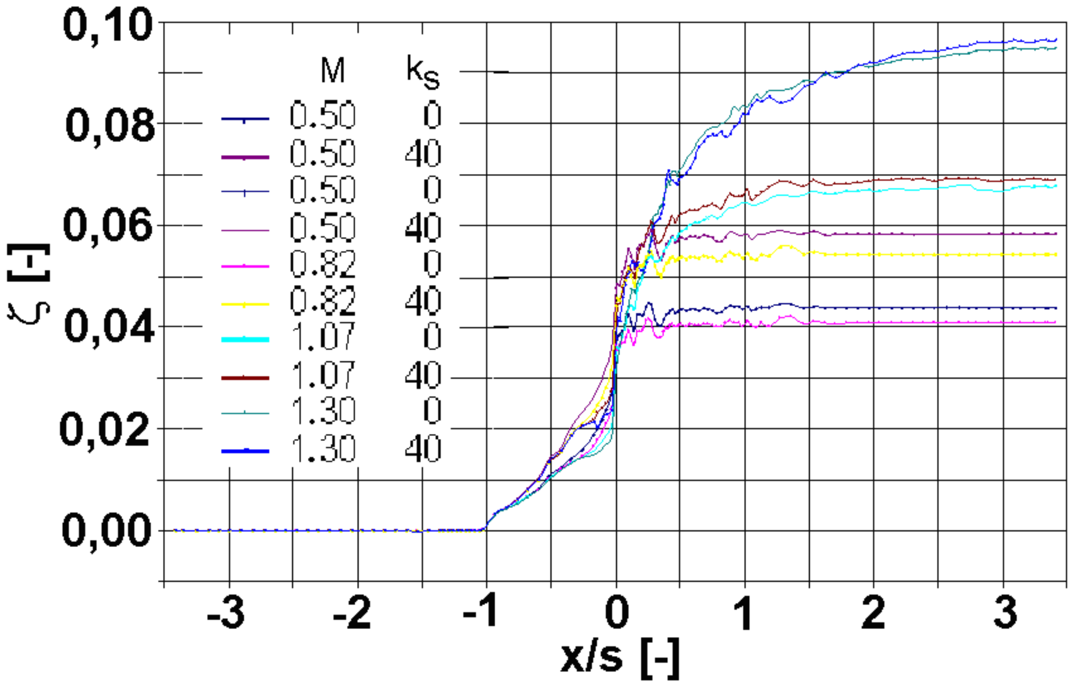

Fig. 11: Loss coefficient with the distance downstream of the blade grid.

5. A surface roughness effect on losses in a turbine stage

The profile losses in a turbine stage are by subsonic flow in comparison with another losses relatively small. Vanes and also moving blades take it’s part on losses. The share of individual grids on the whole loss depends on a type of stage. The enthalpy drop in vanes and moving blades of the impulse stage differs from the enthalpy drop distribution in the reaction stage.

Since profiles of a blade cascade doesn’t correspond with a plane desk and the definition of Reynolds number for the stage isn’t the some as for a desk, the value of transient Reynolds number of the turbine stage will be also different. There is very important by all experiments with the turbine stages to known the value of Reynolds number. The ranges of Reynolds number in an aerodynamic wind tunnel and experimental steam turbines are limited. Reynolds number appears in steam turbines in a range $Re = 10^5 \div 10^7$. The higher values correspond with the operation in HP part of steam turbine and the lower ones can be expected in LP parts. The surface roughness can mainly effect the efficiency of HP parts of steam turbines. Relatively short blades are used in HP cylinder. The share of end wall losses in this regime is more expressive than in other parts of turbine. We can expect that the surface roughness will have also a certain influence on the end wall losses.

The experiments with stages of different aspect ratio and forming of blades were performed. The same profiles tested in the aerodynamic wind tunnel are used. The original roughness with Ra = 0.8 was after sand blasting changed to Ra = 9. The measured data are depict in Fig. 12.

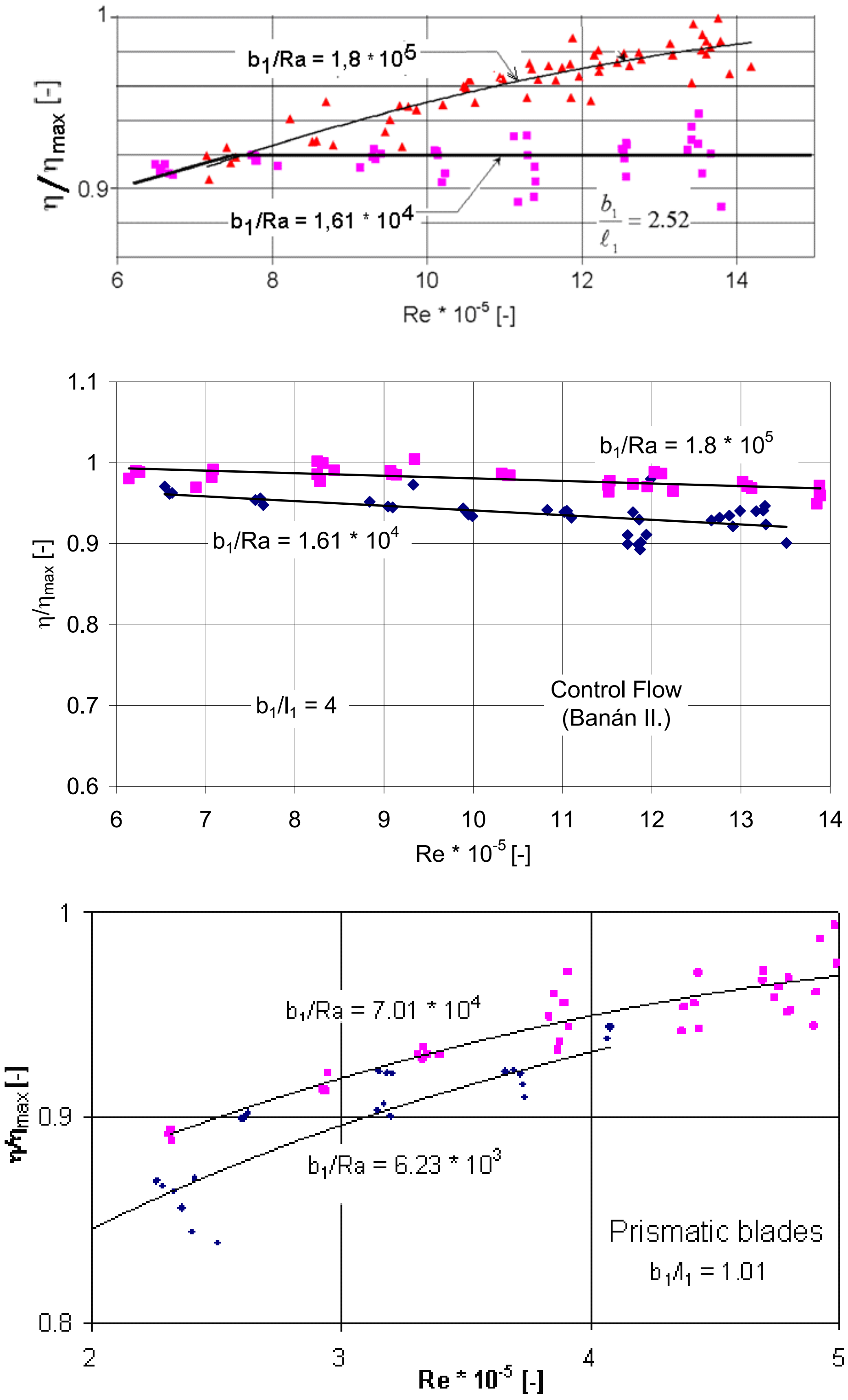

Fig. 12: Thermodynamic efficiency of several stages.

The thermodynamic efficiency of the stage with the reverse aspect ratio $b_1/l_1 = 1.01$ is influenced by lower value of Reynolds number ($b_1 = 70$ mm, $Re < 6 * 10^5$). The prismatic blades were used in this case. The efficiency was decreasing for about 3.5 % after application of roughened surface. The stage with reverse aspect ratio $b_1/l_1 = 2.52$ has chord $b_1 = 145$ mm. Vanes are shapes after Compound Lean rules. The moving blades are of prismatic arrangement. Reynolds number was changed in the range from $Re = (6 \div 10) * 10^5$. The maximum thermodynamic efficiency wasn't in this case received. The effect of surface roughness on efficiency is substantial and represents several percent. By the stage with very short blades ($b_1/l_1 = 4$) Reynolds number doesn't shows such effect that was achieved in previous cases. The efficiency of turbine stage is against expectation with increasing Reynolds number slowly decreasing. The Control Flow of steam with the shape modification of vanes and moving blades was use by this stage. The end wall losses have the significant effect on the final level of thermodynamic efficiency. The transient Reynolds number is shifted to lower values by decreasing of blade aspect ratio. The increased surface roughness effects not only profile losses but also end wall losses. The surface roughness and Reynolds number influence on end wall losses can't be of the same proposition know for profile losses. That would be useful to devote the new experiments to testing of end wall losses by different Reynolds number and surface roughness.

6. Conclusions

- The common knowledge about the influence of Reynolds number and the surface friction on the local skin friction coefficient derived for the plane desk are acceptable for turbine profile, but the exact values are necessary to receive with the help of experimental investigation.
- Increased blade surface roughness plays more significant role in HP parts of steam turbines where appears higher values of Reynolds numbers.
- The surface roughness on suction side of profiles influences mainly the profile losses. Higher roughness on the suction side only on a strip close to the leading edge can increase the turbulence intensity and reduce the profile losses.
- The increased roughness makes thicker boundary layer on both sides of profiles by transonic flow. In the blade to blade passages are the losses by increased surface roughness reduced. The final loss is a function of a distance from the threading edge by the transonic flow.
- The shape modifications the surface roughness and the blade aspect ratio influence the value of transition Reynolds number.
- Their is necessary to find independent criterion for evaluation of surface roughness on the end wall losses.

Acknowledgements

The paper was prepared with the research project financed by the Ministry of Industry and Trade in Czech Republic (project FT-TA5/067)

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