REDUCTION METHODS OF SECONDARY FLOW LOSSES IN STATOR BLADES: NUMERICAL AND EXPERIMANTAL STUDY

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ABSTRACT

This paper examines the perspective design solutions for the secondary flows intensity reduction in the root and peripheral areas of the vane cascade. Increase of the aerodynamic efficiency is achieved by the special finning of internal shroud surface of the vane passage with curvilinear fins having a small height.

A study was conducted to analyze the different types of finning on the basis of three-dimensional simulation (CFD). It considers variations with different number, height and shape of used curvilinear fins. In the process of optimization, the best case, which allows to reduce the secondary flow losses by 10-15 %, was obtained.

Experimental studies of two vane cascade models were carried out on the aerodynamic test bench. First model was a vane base-type; second model was based on the optimal geometry obtained according to the results of three-dimensional simulation. Experimental studies make possible to confirm the proposed solution efficiency.

KEYWORDS

SECONDARY FLOWS, VANE CASCADE, TURBINE STAGE, EFFICIENCY, FINNING

NOMENCLATURE

Latin Symbols

b	chord
l, $\bar{l}$	length, the relative length
t, $\bar{t}$	pitch, the relative pitch
Re_b	Reynolds number

Greek Symbols

α_0	inlet flow angle
α_1	vane exit angle
$\zeta_к$	secondary flow loss coefficient

Abbreviations

CFD	Computational Fluid Dynamics
HPT	high-pressure turbine
RANS	Reynolds-averaged Navier-Stokes

INTRODUCTION

Adoption of improved production technologies is inextricably linked with the emergence of new or dynamic modernization of the existing power generating units. In this connection, due to limited natural resources, special attention is paid to methods of increasing the efficiency of electrical energy production.

Efficiency of the modern power steam turbines has a quiet high value. But, nevertheless, the possibility of its increase is still a priority and urgent task today. Power steam turbine efficiency growth as a whole can be achieved by improving its part separately. For example, high – pressure turbine (HPT), performance characteristics of which is largely determined by secondary losses.

Secondary flow losses in turbine cascades associate with the presence of flow skin friction on the endwall surfaces and also with formation and development of secondary flow vortices. Thus, knowing factors affect the nature and intensity of the secondary flows in a blade passage, it becomes possible to rule their formation and, consequently, to reduce secondary losses in profile cascade.

Secondary flow problem studying are reflected in works of many scientists. Formation mechanism of secondary flow vortices near the blade trailing edge was investigated by Klein A. (1966), Langston L.S. et al (1977), Sieverding C.H. (1984), Doerffer P.P. et al (1994), Lampart P. (2009), Tian Q. et al (2004). In the work (Zi-Ming F. et al, 2015), it is proposed to reduce aerodynamic losses and increase the efficiency of profile cascade by blade geometric parameters optimization. Total energy loss coefficient reduction achieved using this approach is 0.55 %.

Great attention to consider topic is also given in book of Zaryankin A.E., which deals not only with the theoretical aspects of the secondary flows formation as well as names a number of ways to reduce secondary flow vortices intensity.

The possibility to use the longitudal fins in profile cascade was presented in the paper of Zaryankin A.E. et al (2016). According to obtained experimental data fins installation allows to reduce the ratio of total energy loss coefficient in the consider cascade from 3.6 to 2.7 %.

Another possible constrictive variant of turbine profile cascade modernization presents in the patent SU 299658, F 01D 1/04 (1971), in which it is proposed to design bandages with longitudinal grooves.

THEORETICAL BACKGROUND

In general case, total energy losses in profile cascade consists of profile and endwall components.

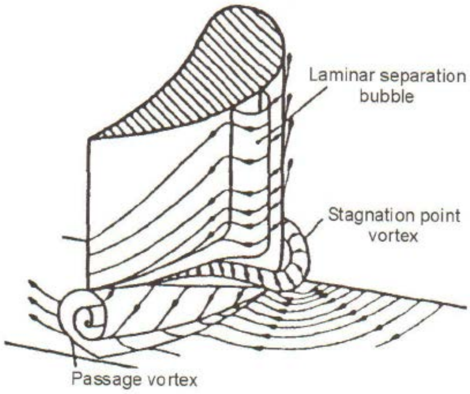
Profile loss is the loss due to skin friction on the blade surface, due to finite thickness of the blade trailing edge and to the transition to supersonic speeds (wave losses). The profile loss magnitude is almost completely determined by the blade passage geometry. The endwall loss also depends on characteristics of flow traveling across the curved profile passage.

Endwall losses are the losses caused by flow friction on the endwall surfaces, by secondary flow vortices formation in the blade passage and by presence of radial “compensation” flows in profile cascade.

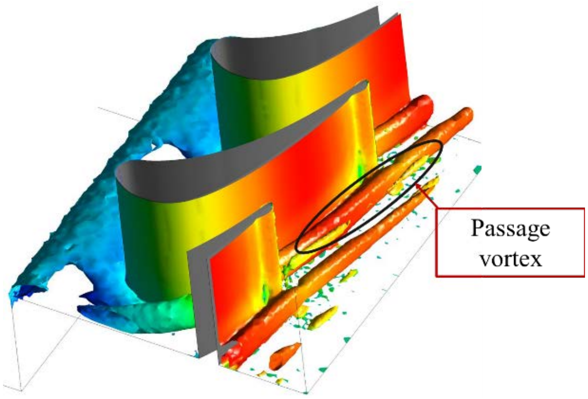
Structure of secondary flows is quiet complicated and controversial, mechanism of their formation is still unknown exactly. At present, the main adopted hypothesis says that secondary flows are vortices occur as a result of boundary layers and curvature of the passage and cause some part of fluid to move in direction other than the principal direction of flow.

The secondary flows occur in a curved channel due to the mass centrifugal forces appearance acting on the particles of liquids and gases moving along curved streamlines. Accordingly, the response occurs in the form of transverse pressure gradients appearance balancing the centrifugal forces. The balance break down on the end walls due to lower velocities in the boundary layers of these surfaces and the transverse secondary flows occur. The boundary layer’s moving along the passage rolls up into the passage vortices entraining mainstream fluid. Additionally to vortices formation across passage, the endwall boundary layer rolls up in the front of a blade and forms horseshoe vortex, named so because of its shape. The horseshoe vortex then distributes itself about pressure and suction side of the profile producing pressure-side leg and suction-side leg of horseshoe vortex. According to theory proposed by Langston L.S. et al (1977) pressure-side leg of the horseshoe vortex is a part of passage vortex and suction-side leg is known as counter vortex.

In Fig. 1, 2 images of the secondary flows according to theoretical investigations (Fig. 1a, 2a) and obtained during CFD-modeling (Fig. 1b, 2b) are presented. In these images, the main components of secondary flow vortices are clearly visible: passage vortex (Fig. 1), which is swept across passage under the action of cross-passage pressure gradient; counter vortex; horseshoe vortex (Fig. 2), formed in the front of a blade.

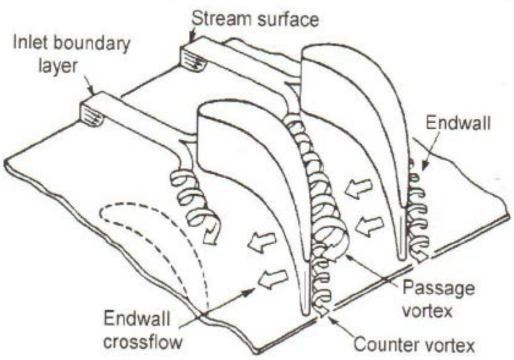


(a) schematic diagram (Klein A., 1966)

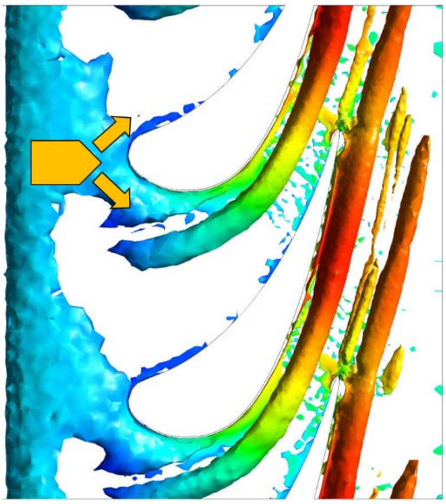


(b) CFD-modeling results

Figure 1: Secondary flow vortices in a blade passage



(a) schematic diagram (Langston L.S. et al, 1977)



(b) CFD-modeling results

Figure 2: Secondary flow vortices in a blade passage

Complex structure of secondary flows does not allow to obtain reliable and common theoretical description. However, for practical purposes it is necessary to be able to estimate secondary losses in a certain profile cascade, and also to define factors determining this value. Therefore, several semi-empirical formulas were obtained on the basis of various experimental data. One of them is given below (Zaryankin A.E., 2004).

$$\zeta_K = \frac{0.13}{\mathrm{Re}_b^{0.2} \cdot \bar{l}} \left[1 + B\left(1 + \frac{ctg\alpha_0}{ctg\alpha_1}\right)^2 \bar{t}^{-2} \cos^2 \alpha_1 \right], \qquad (1)$$

where $\bar{l} = \frac{l}{b}$ is a relative profile length; $\bar{t} = \frac{t}{b}$ is a relative profile pitch; *B* is a coefficient depending on the flow regime and type of the cascade (determined experimentally).

Thus, analyzing Eq. (1), it can be concluded that ζ_K is a function of geometric ($\alpha_0, \alpha_1, \bar{t}$) as well as operating parameters of the blade cascade. A significant influence on numerical value of secondary flow loss coefficient is made by relative blade pitch $\bar{t}$, since the dependence of ζ_K from $\bar{t}$ is quadratic. For example, for vane cascade according to Eq. (1), when $\bar{t}$ decreased two times, the value of ζ_K decreased at 19.6 % (all of other parameters remained constant).

The most ordinary and obvious way, which allow to reduce relative blade pitch is an installation of a large number of blades in the same turbine stage cascade. But, it is easy to see that this method can lead to some undesirable consequences, including: increasing of metal consumption, increasing cost of a unit, a considerable profile losses growth.

Another possible way is to “simulate” the presence of additional profile (or profiles) within boundary layer by installation of small-height longitudinal fins on inner side of bandage (or bandages) in blade passage. This solution lets preventing a significant growth of other components of energy losses; apart from it, it can be applied not only to new units, but also during the modernization of exciting equipment. Nevertheless, it is necessary to point out, that fins installation may increase endwall surface friction loss.

BOUNDARY CONDITIONS, COMPUTATIONAL DOMAINS AND PARAMETERS

Numerical and experimental study of vane cascade was carried out to prove theoretical hypotheses.

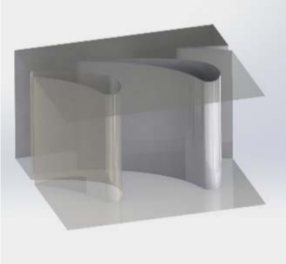
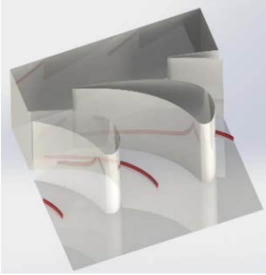
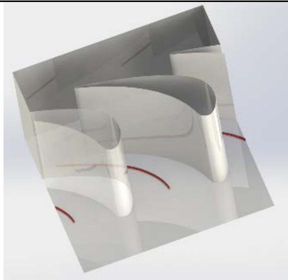
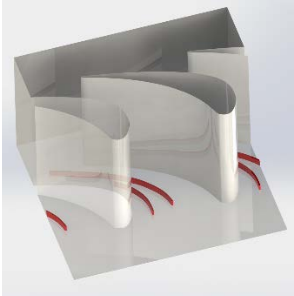
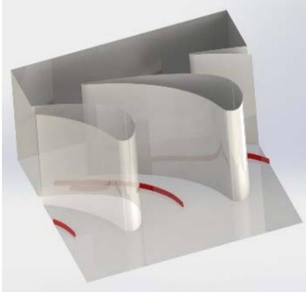
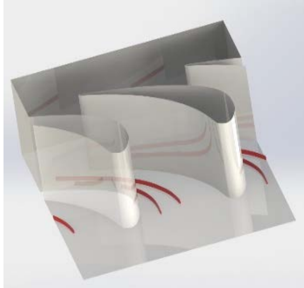
As a basis for experimental model, vane profile C 90-12-A was selected. By repetition of this profile planar vane cascade was formed (with a fixed pitch *t* = 35 mm). The height of cascade was 40 mm. Ahead cascade inlet there was a chamber, which provided an unequal velocity profile before vanes. Presence of such uniform velocity vector field has a meaningful impact on the characteristics of formed secondary flow vortices (Koschichow D. et al., 2015), and therefore it must be modeling in research. Main geometric parameters of experimental models are presented in Tab. 1.

Table 1: Model main geometry

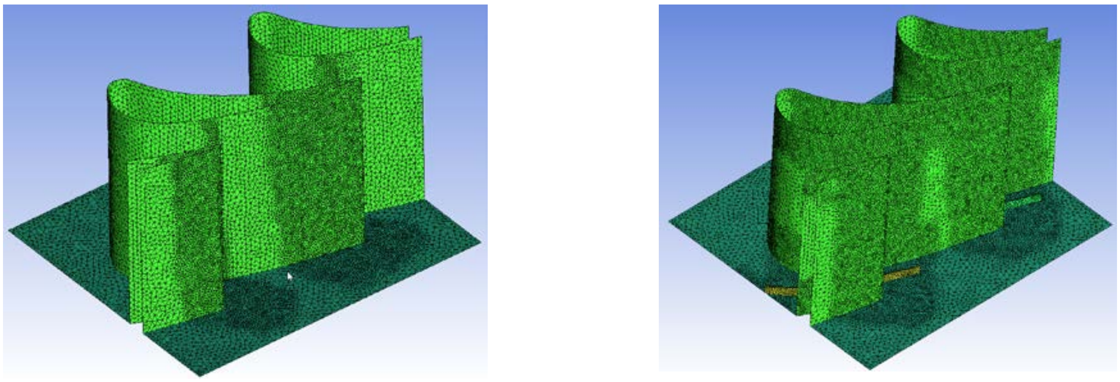
Parameter	Value
Vane cascade height	40 mm
Vane chord	50 mm
Vane pitch	35 mm
Inlet chamber height	88 mm
Inlet chamber length	70 mm

Various cases of fins installation were investigated due to impossibility of accurate theoretical predictions of the exact geometric parameters of fins system, providing the greatest vane cascade efficiency improving (Tab. 2).

Table 2: Cases investigated

			
Baseline	Case M1: one rectangular fin with a height of 2 mm, a width of 0.5 mm on the upper and lower bandages	Case M2: one rectangular fin with a height of 3 mm, a width of 0.5 mm on the upper and lower bandages	Case M3: one rectangular fin with a height of 1 mm, a width of 0.5 mm on the upper and lower bandages
			
Case M4: three rectangular fins with a height of 2 mm, a width of 0.5 mm on the upper and lower bandages	Case M5: one whole and one piecewise rectangular fins with a height of 2 mm, a width of 0.5 mm on the upper and lower bandages	Case M6: one triangular fin with a height of 2 mm, a width of 0.5 mm on the upper and lower bandages	Case M7: one whole and one piecewise triangular fins with a height of 2 mm, a width of 0.5 mm on the upper and lower bandages

Computational meshes were made in ANSYS ICEM. All investigated meshes are periodical, unstructured, consisting of tetrahedral (main flow area) and prismatic (boundary layer regions) elements. The value of the y^+ parameter is lower than 2. Computational meshes for Baseline case and Case M1 are shown in Fig. 3.



(a) Baseline (b) Case M1

Figure 3: Three-dimensional meshes of computational domain

Total number of mesh elements for all cases was around 4-5 million. The mesh resolution in the fins area was 0.6. There are 13 prism layers followed by 5-6 tetra cells along the fin's height. The boundary layer total thickness in the models was 0.96 mm. Prism meshing parameters were following: initial height 0.0029 mm, height ratio 1.39 (wb-exponential growth law).

Numerical solution of RANS equation system was carried out in ANSYS CFX. Used turbulence model – k-omega with scalable near-wall function. All model walls are adiabatic, no slip. Other boundary conditions are presented in Fig. 4; rest cases parameters – in Tab. 3.

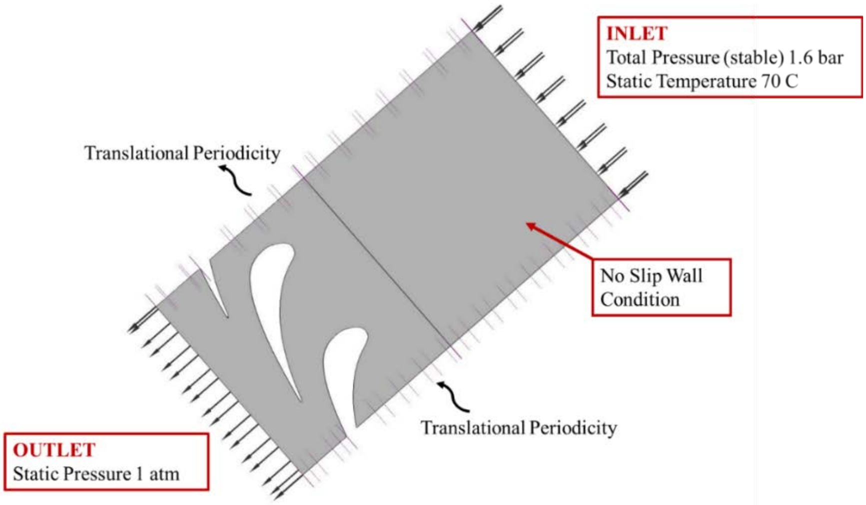


Figure 4: Boundary conditions

Table 3: Cases main parameters

Parameter	Value
Domain fluid	Air
Inlet total pressure	0.16 MPa
Inlet fluid temperature	343 K
Outlet static pressure	0.1 MPa
Outlet flow theoretical velocity	290.4 m/s

RESULTS ANS DISCUSSION

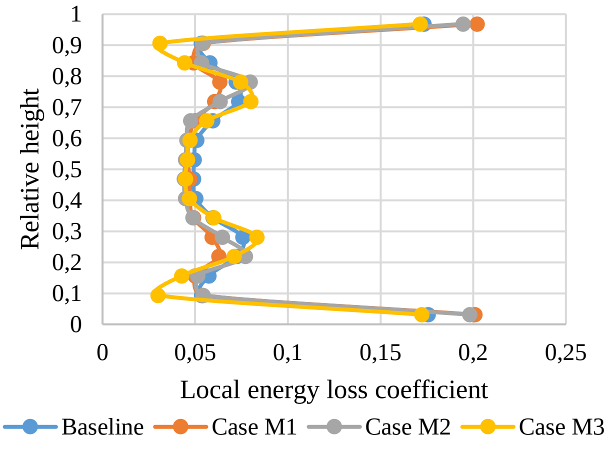
Quality dependences of the total energy loss coefficient in vane cascade from various factors: fin height, fins layout within passage and fin shape were obtained during numerical experiment.

Influence of fin height

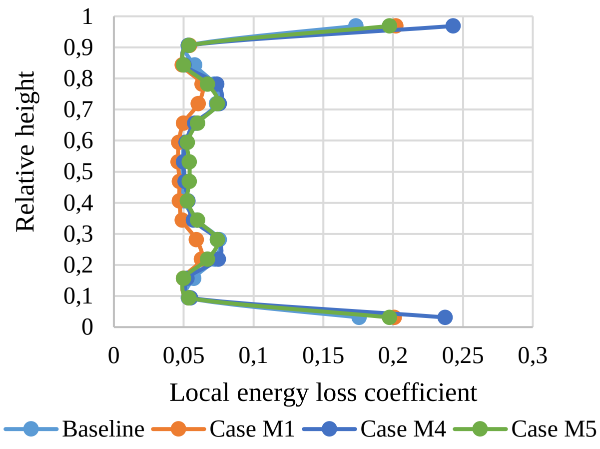
Distribution of local energy loss coefficient along vane height for different fin height values is shown in Fig. 5a. The greatest positive effect is observed for 2 mm height fins (Case M1). In this case, there is a decrease in secondary flow vortices formation in the trailing edge region, which, in turn, increases vane cascade efficiency and reduces total energy loss coefficient in it at 7.78 %.

For higher fins (3 mm, Case M2) a significant role are being played by fins aerodynamic resistance. Fins system, in this case, are outside of the upper limit of boundary layer and promote energy losses growth due to flow friction on the endwall surfaces. Total energy loss coefficient reduction is at 4.47 %.

Small fin height (1 mm, Case M3) also does not lead to a noticeable improvement of the vane cascade performance characteristics. Fig. 5a shows that this geometry does not reduce intensity of secondary flow vortices formation.



(a) for different fin height



(b) for different fins layout

Figure 5: Distribution of local energy loss coefficient along the height of studied vane model

Influence of fins layout within vane passage

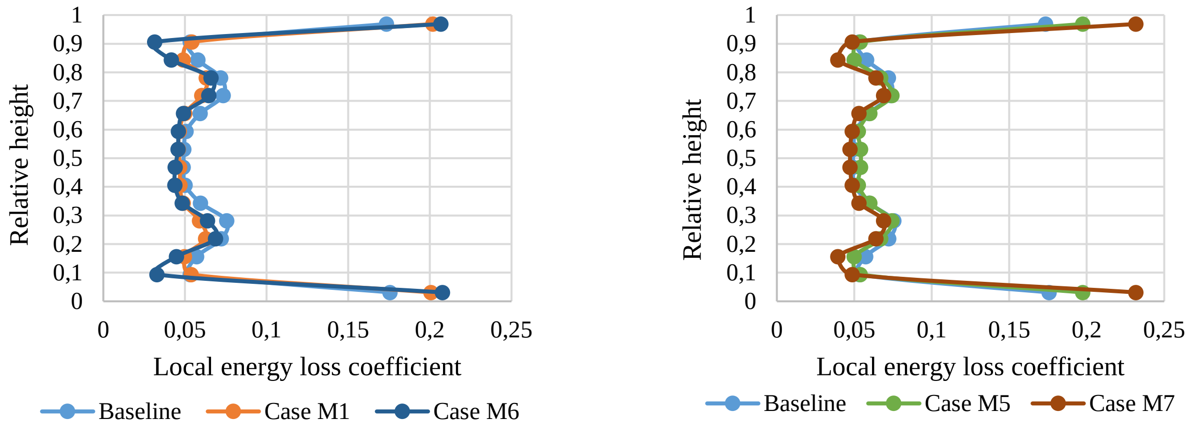
Different fins layout within vane passage have a great impact on total energy loss value (Fig. 5b).

Accommodation of three rectangular fins height of 2 mm (Case M4) in one passage increases (at 4.47 %) total energy loss coefficient compared to Baseline. Installation of one whole and one piecewise fins (2 mm, Case M5) has a little positive effect on mainstream characteristics and almost does not lead to decreasing of secondary flows formation; total energy loss coefficient remains the same. The most significant improvement of vane cascade performance is observed by the one rectangular fin (2 mm, Case M1) within profile passage. In this case, there is also the reduction of two symmetric vortex region and the improvement of core flow structure.

Influence of fin shape

Fin shape largely determines aerodynamic resistance of the fins system. In this numerical investigation rectangular and triangular fins were examined. Result of a study is presented in Fig. 6 for different fins layout: for one fin within vane passage (Fig. 6a) and for one whole and one piecewise fins (Fig. 6b).

In all cases triangular fins shows the best performance. One triangle fin height of 2 mm (Case M6) allows to decrease total energy loss coefficient in vane cascade at 11.9 % compared to Baseline.



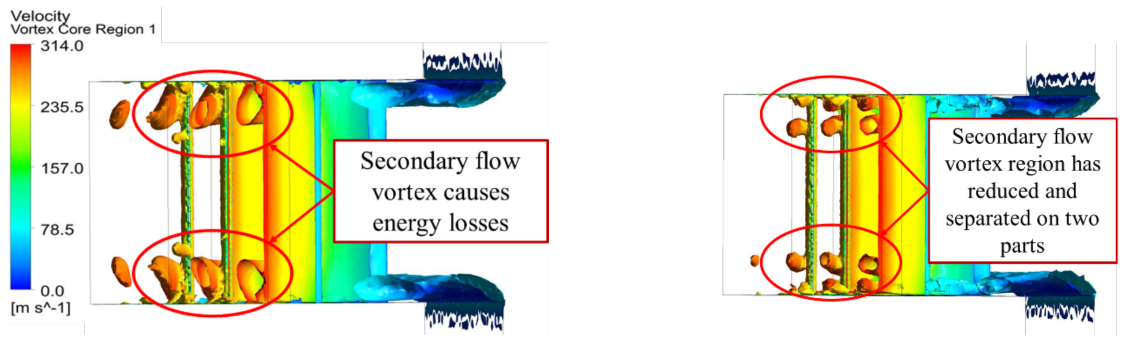
(a) for one fin within vane passage

(b) for one whole and one piecewise fins within vane passage

Figure 6: Distribution of local energy loss coefficient along the height of studied vane model

Efficiency of the finning to reduce energy losses in vane cascade

Comprehensive analysis of numerical experiments results showed the fins system efficiency. Fig. 7 depicts the difference in flow behavior near the vane trailing edge region: installation of curvilinear fins led to the decrease of the secondary flows area and splitting of one large vortex into two small vortices.

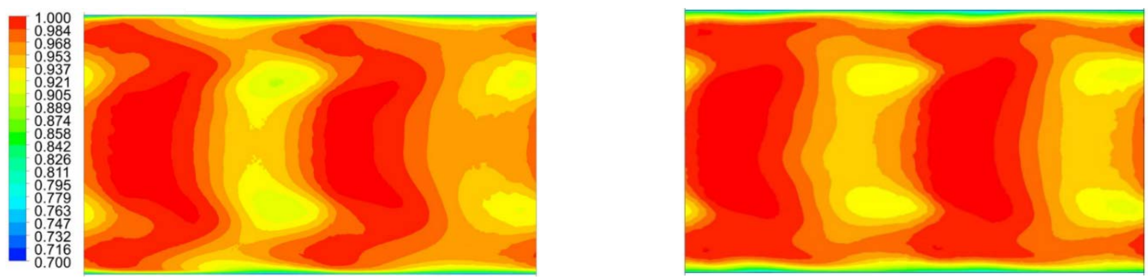


(a) Baseline

(b) Case M1

Figure 7: Secondary flow vortices in computational models

Total pressure coefficient contour plot on cascade inlet also confirmed finning efficiency (Fig. 8).



(a) Baseline

(b) Case M6

Figure 8: Total pressure coefficient contour plot on the profile cascade outlet

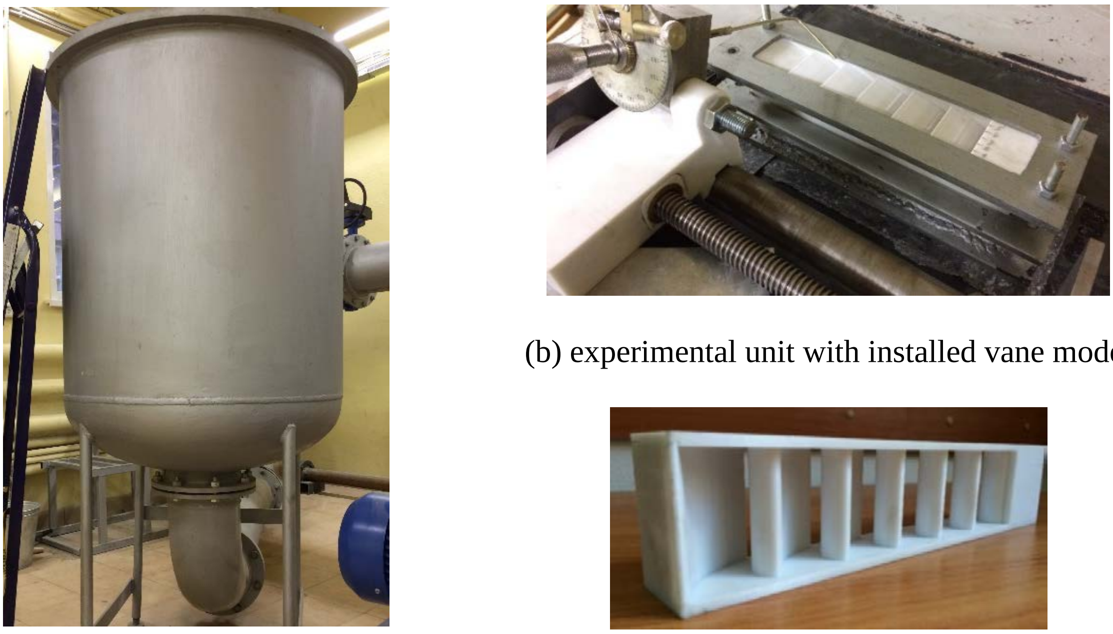
One triangle fin (Case M6) and one whole and one piecewise fins (Case M7) showed the minimum energy loss in profile passage.

Fins system geometry, corresponding to the most efficient design, was taken for further investigation: profile passage with one triangle fin height of 2 mm (Case M6).

EXPERIMENTAL INVESTIGATION

Two planar vane cascade models were used in experimental investigation: Baseline model without fins (Exp. Case 1, Fig. 9b) and model with one triangle fin height of 2 mm on both bandages.

Studies were carried out at experimental unit shown in Fig. 9a, 9b. Atmospheric air was delivered by blower. Reynolds number Re_b was equal to 22 000 in all experiments.



(b) experimental unit with installed vane model

(a) experimental unit

(c) experimental model (Exp. Case 1)

Figure 9: Experimental unit and experimental model

Distribution of local energy loss coefficient along the height of vane model shown in Fig. 10 was obtained as a result of experimental tests.

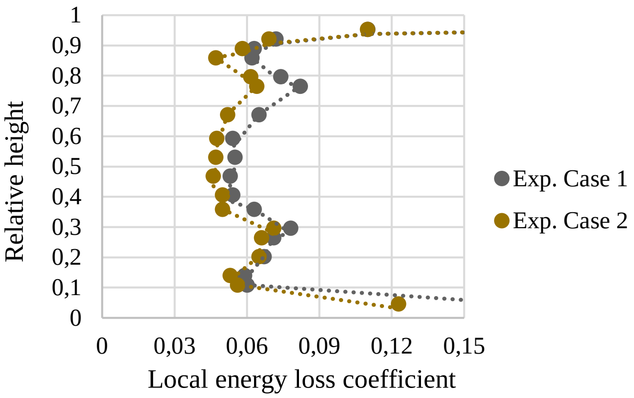


Figure 10: Distribution of local energy loss coefficient along the height of vane model obtained during experiments

The experimental data analysis confirmed the positive effect of fins installation in vane passage. Presence of small-height longitudinal fins on the inner side of upper and lower bandages reduces secondary flows formation intensity, lowers total energy loss coefficient by 11.5 % and improves the efficiency of a turbine stage.

CONCLUSIONS

The efficiency assesment of installation of the small-height longitudinal fins in vane passage were carried out by CFD-modeling and physical experiments.

Results of numerical study allowed to conclude not only about the proposed solution efficiency, which turned out to be quite significant for some investigated models; but also about the effect of different fin system parameters (fin height and shape, fins layout within vane passage) on total energy loss coefficient in profile cascade.

Maximum decrease of total energy loss coefficient was observed for one triangle fin height of 2 mm (Case M6), installed on the inner side of lower and upper bandages, and was 11.9 %.

Experimental study definitively confirmed numerical investigation results. According to physical experiments data the reduction of total energy loss coefficient of the finned model compared to Baseline was 11.5 %.

Thus, it can be confidently said that installation of small-height longitudinal fins system on the inner side of upper and lower bandages really improves efficiency of the turbine stage by reducing the amount of energy losses in vane cascade.

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REFERENCES

Klein, A. (1966). *Untersuchungen über den Einfluß der Zuströmgrenzschicht auf die Sekundärströmungen in den Beschaufelungen von Axial turbinen*. Forschung im Ingenieurwesen A, 32(6), 175-188.

Langston, L.S., Nice, M. L., Hooper, R.M., (1977). *Three-dimensional flow within a turbine cascade passage.* Journal of Engineering for Power, 99(1), 21-28.

Sieverding, C.H., (1984). *Resent progress in the understanding of basic aspects of secondary flow in the turbine blade passage.* American Society of Mechanical Engineers, 29-th International Gas Turbine Conference and Exhibit, Amsterdam, Netherlands.

Doerffer, P.P., Amecke, J., (1994). *Secondary flow control and streamwise vortices formation*. International Gas Turbine and Aeroengine Congress and Exposition. American Society of Mechanical Engineers, The Hague, Netherlands.

Lampart, P., (2009). *Investigation of endwall flows and losses in axial turbines. Part I. Formation of endwall flows and losses*. Journal of Theoretical and Applied Mechanics, 47(2), 321-342.

Tian, Q., Simpson, R.L., Tang, G., (2004). *Flow visualization on the linear compressor cascade endwall using oil flows and laser Doppler anemometry*. Measurement Science and Technology, 15(9), 1910.

Zi-Ming, F., Jin-Dong, Z., Hui-Bin, G., (2013). *Aerodynamic performance of nozzle blade cascade with meridian-shrank endwall profile*. Journal of Applied Sciences, 13(7), 1052.

Zaryankin, A.E., (2014). Mechanics of incompressible and compressible fluids. MPEI, Moscow, Russia. (in Russian).

Zaryankin, A.E., Rogalev, N.D., Rogalev, A.N., Garanin, I.V., Osipov, S.K., Grigoriev, E.Y., (2016). *Control valves and cascades for the first stages of turbines with ultrasupercritical steam parameters.* Thermal Engineering, 63(6), 422-429.

Kuznetsov, N.D., Deitch, M.E., Klebanov, A.G., (1971). *Turbomachines blade cascade*. Patent SU 299658, F 01D 1/04.

Moustapha, H., Zelesky, M.F., Baines, N.C., Japikse, D., (2003). *Axial and radial turbines.* Vermont, USA: Concepts NREC.

Koschichow, D., Fröhlich, J., Ciorciari, R., Niehuis, R., (2015). *Analysis of the influence of periodic passing wakes on the secondary flow near the endwall of a linear LPT cascade using DNS and U-RANS*. Proceeding of the 11-th European Conference on Turbomachinery, Fluid dynamics & Thermodynamics, Madrid, Spain.