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NEW METHOD AND ALGORITHM OF THREE-DIMENSIONAL TURBINE GUIDE BLADE RIM OPTIMIZATION

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ABSTRACT
The new method and algorithm of three-dimensional turbine guide blade rim optimization were proposed using CFD-calculations, guide blade deformation and reasonable computation time consuming optimization approach.

Verification of three-dimensional CFD-calculations results are presented by comparison with experimental data. The reasonableness of the isolated guide blade rim optimization of a turbine stage is justified. Two methods of the complex tangential lean implementation are compared. The parametric model is developed allowing conservation of the mass flow rate through the blade passage during optimization process. Both a bowing method and computational grids construction are realized in specialized program *TOpGrid*. The gained grids has been written in format *CGNS* (*CFD* General Notation System). The optimization approach is grounded on a combination of the DOE theory and Monte-Carlo method. The algorithm of optimization of guide blade rim is described. The examination of aerodynamic optimization efficiency with the developed algorithm of a guide blade rim at different *a/l* (*a*-throat of the channel, *l*-height of a blade) was carried out . The analysis of the results of the computation and physical explanation of reasons of a turbine blade passage efficiency rise is given.

NOMENCLATURE AND GLOSSARY

ζ_n	losses in nozzle vane
ζ_b	losses in blade
ζ_o	overall losses in the turbine stage ($\zeta_n + \zeta_b$)
eff	aerodynamic efficiency (1-ζ)
P^*_1	inlet total pressure
T^*_1	inlet total temperature
P^*_2	outlet total pressure
P_2	outlet static pressure
M_{2is}	outlet isentropic Mach number
M_2	outlet Mach number
k	isentropic exponent
Re	Reynolds number
init	initial
opt	optimal
b	blade chord
t	pitch
l	blade height
l_c	current hub to shroud distance
$\bar{l}$	relative blade height
a	blade passage throat
β_s	blade profile setting angle
D_m	blade rim mean diameter
Y_0, Y_h, Y_1, Y_s	stacking curve parameters
$\Delta\beta_s$	amendment of blade profile setting angle
ε	criterion of discrimination
NURBS	non-uniform rational B-spline
CFD	computational fluid dynamics
CGNS	*CFD* general notation system
DOE	design of experiment
OMM	original mathematical model
FMM	formal macromodel
B_i	target function *FMM* coefficients
C_i	restriction function *FMM* coefficients

$$\zeta = \frac{2}{(k-1)}\frac{1}{M_{2is}}\left[\left(\frac{P^*_1}{P^*_2}\right)^{\frac{k-1}{k}} - 1\right]$$

INTRODUCTION

In modern turbine construction increase of efficiency of turbine flow path (apart from improvement of blade cascade profiles) is carried out by turbine blade three-dimensional optimization. The methods of computational fluid dynamics (*CFD*) are used as the basic tool of flow modeling in turbine blade rims. Such three-dimensional optimization allows increasing efficiency of blade rims due to diminution of total losses by deformation of blade, including various sorts of leaning, twisting, scaling, etc. [1, 2, and 3].

In presented paper at a statement of problem of the guide blade rim spatial optimization was tasked:

- To develop a method and algorithm of turbine stage guide vanes optimization of the high-pressure cylinder, allowing its use with various *CFD-solvers*;
- To confirm the reliability accepted computational method by comparison results of computation with experimental data;
- To verify legitimacy of a problem statement of separately taken turbine guide blade rim optimization, instead of in structure of a turbine stage;
- Strictly to hold out the mass flow rate during the optimization.

VERIFICATION OF THREE-DIMENSIONAL NUMERIC COMPUTATIONS

All computations of optimization research were carried out in three-dimensional statement with ANSYS *CFX*.

Object of computation was flow ($P*_1$=113 kPa; $T*_1$=393.15 K; P_2=100 kPa; M_2=0.4; Re=4.2×10^5) in a guide blade cascade TN-2 type with following parameters: a chord b=45 mm; the relative blade pitch t/b=0.57; height of the blade l=40 mm; the distance from output edges to plane of measuring come to 2.7 mm. In conformity with graphics of efficiency change in the line of cascade height (Fig. 1) it is
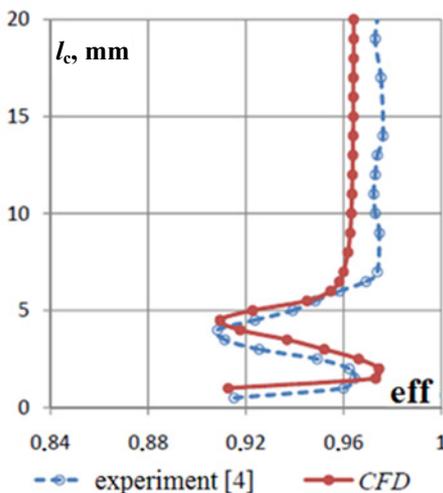

Figure 1. Efficiency distribution along blade height

visible, that result of *CFD* computation and experiment sufficiently coincide both qualitatively and quantitatively. Results of *CFD* calculation well enough reproduce flow structure in a turbine cascade that has allowed using them in an optimization problem.

Strictly speaking, optimization of guide blade rim and rotor blade rim it is necessary to carry out in the structure of a stage. However even single calculation of working medium flow in a turbine stage essentially extends a computation time. Duration of one computation can make from several up to dickers hour. For checkout of legitimacy of separately taken distributor optimization its optimization separately from a stage has been conducted. Flow conditions and geometry of a stage matched to conditions of an experimental research [5] on the experimental air one-stage turbine TV-3. The gained optimized guide blade rim was installed in a turbine stage, with subsequent *CFD* calculation of flow in whole turbine stage at appropriate boundary conditions. The stage was computed without overlap and without taking into account leakages of a working medium with the purpose of exclusion of their effect and detection in the pure state a gain on blades losses of the stage. Results of computation of the initial stage and a stage with the optimized distributor are given in Table 1. In the table losses of a kinetic energy in the guide blade rim (ζ_n), losses in the rotor blade rim (ζ_b) and overall losses (ζ_o) at the stage

Table 1. Stage computation results

Losses Variant	ζ_n, %	ζ_b, %	ζ_o, %
Initial	4.494	7.962	12.456
Optimal	4.379	7.732	12.111

without taking into account losses with an exit velocity are given. On the gained data it is visible, that installation in a stage isolated optimized distributor has given the positive effect. It is possible to reduce losses, both in the guide blade rim and rotor blade rim and in a stage as a whole.

Carried out computation examination have confirmed legitimacy of a statement of the isolated guide blade rim optimization problem.

STATEMENT OF OPTIMIZATION PROBLEM

In the paper under consideration the curving of a blade on height was carried out by a shifting tied up to stacking line cross-sections (blade profiles) in a tangential direction. On them the three-dimensional blade with usage of non-uniform rational B-splines *(NURBS)* was reproduced.
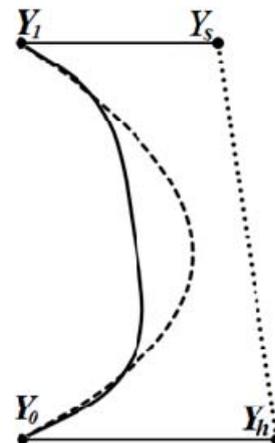

Figure 2. Parametrical stacking curves

Blade profile during optimization did not vary.

The initial object of optimization is the isolated turbine guide blade rim with cylindrical blades. Blade profiles at a root and on periphery did not displace during optimization. The varied parameters uniquely determining the shape of a blade vane represent a blade displacement ratio (to the length of the blade) in a tangential direction for root Y_h, for blade tip Y_s and also a blade angle of rotation. On a Fig. 2 two means of a stacking curve construction are presented, first - with usage of simplified Bézier curve of 3-rd order (dash line), second - with usage of simplified Bézier curve of 4-th order with a delimiter (full line) [6]. The mentioned simplification consist in use of the normalized altitude of a blade $\bar{l}$ as parameter of Bézier curve that has allowed to diminish twice quantity of parameters determining the shape of a curve [7]. Formulas on which the stacking curve was determined, are given below (the formula (1) - for modified Bézier curve of the third order, the formula (2) - for modified Bézier curve of the fourth order).

$$P(Y, \bar{l}) = (1 - \bar{l})^3 Y_0 + 3\bar{l}(1 - \bar{l})^2 Y_h +$$
$$+ 3\bar{l}^2(1 - \bar{l})Y_s + \bar{l}^3 Y_1 \qquad (1)$$

$$P(Y, \bar{l}) = (1 - \bar{l})^4 Y_0 + 4\bar{l}(1 - \bar{l})^3 Y_h +$$
$$+ 16\bar{l}^2(1 - \bar{l})^2 Y_m + 4\bar{l}^3(1 - \bar{l})Y_s + \bar{l}^4 Y_1 \qquad (2)$$

where $Y_m = \frac{3}{16}(Y_0 + Y_1)$

In the formula (2) definition of parameter Y_m on the equation, has allowed to gain a stacking curve with a straight-line segment in a mean part of a blade and to diminish quantity of parameters up to two. Y_0 and Y_1 remained constant during optimization.

Samples of the blades and grids, which are gained as a result, are shown on a Fig. 3.

Pending an optimization of a turbine stage or blade rims of a stage it is necessary to stand restriction of mass flow rate of the initial and optimized variants. Specified requirement requires including at least one additional varied parameter providing limitation of the mass flow rate during optimization.

In presented paper as such additional parameter the blade profile setting angle has been accepted, rather its change $\Delta\beta_s$, varying which it is possible to achieve an object in view - to maintain a reference value of mass flow rate.

The plane, where flow parameters were calculated, was accepted on an exit of a blade rim, immediately behind an exit edge of blade.

Thus, the optimization problem is stated as follows:

It is necessary to find such a value of guiding parameters Y_h, Y_s and $\Delta\beta_s$ at which the turbine blade rim has the minimal integral losses of a kinetic energy at the fixed mass flow rate through it.

Deformation and rotational displacement of a blade, build-up of computational domain, its spacing and export to the universal format *CGNS* [8], were fulfilled using specialized, developed on turbine projection chare of NTU «KhPI», program *TOpGrid* [6]. The *CGNS* data format is supported by the most widespread *CFD*-solvers (*CFX, Fluent, ICEM CFD, NUMECA* etc.).

Program *TOpGrid* enables to build the structured *H*-grids in blade passages of a sufficiently arbitrary geometry. Grid crowding can be carried out by exponential or power law, into each of which three variables are incorporated. Changing of these variables it is possible to
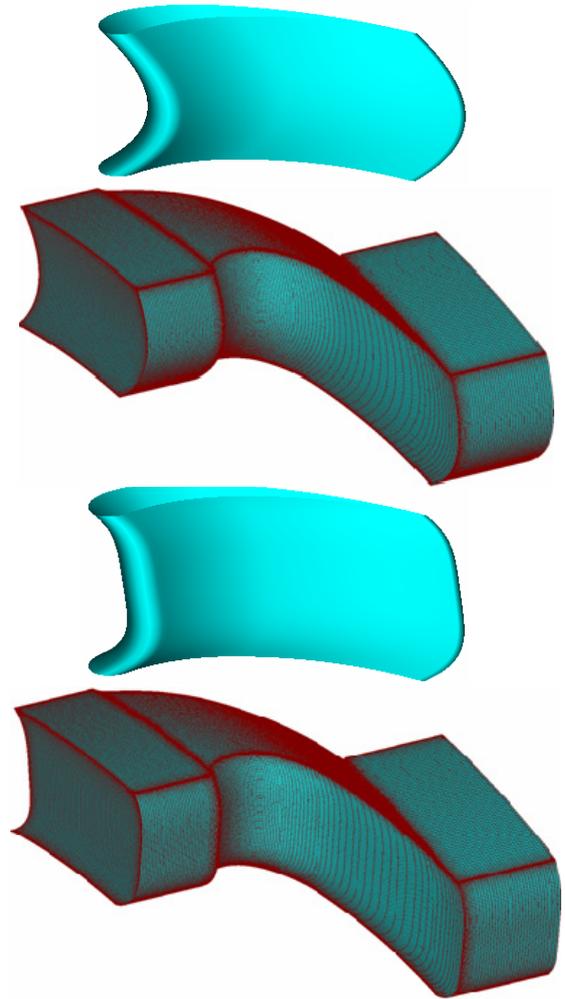

Figure 3. Parametrical turbine blades and grids

influence on a grid inspissations. The basic advantages of program *TOpGrid* account for prompt automatic build of grids for *CFD*-calculations, that is significant at conducting a plenty of computation, possibility of its application in a combination with various *CFD*-solvers and export to the universal *CGNS* format. The choice of grid parameters and a procedure of conducting of computation matched to the guidelines of operation, described in [6].

To resolve the viscous shear layers with sufficient accuracy, the cell widths, along the walls and longitudinal direction of the flow, in the area of boundary layers on the hub, shroud and blade surfaces have been crowding on power law. The value of Y+ was less then 1. No-slip and adiabatic wall conditions have been accepted on solid walls. A periodic boundary condition is used in the circumferential direction. The total pressure and total temperature were set at inlet boundary condition as well as static pressure was taken at outlet boundary condition.

All numerical calculations were spent with use of TVD discretization scheme with high resolution (second order precision) and SST turbulence model.

SELECT OF AN OPTIMIZATION METHOD

As it is known process of optimization requires carrying out from dicker up to hundreds and even thousand computations depending on an optimization method. Preliminary computation research has shown that target function has some noises stipulated by an accuracy of computations that expels usage of optimization techniques demanding derivatives calculation. One of the most universal optimization method which are not demanding evaluation of derivatives or any kind of limitations on target function is the genetic algorithms and Monte-Carlo methods with various random sequence of points, but requiring carrying out from hundreds up to thousand computations. Duration of one *CFD* computation in our problem can last some hours even with using modern enough PC.

Therefore the solution of an assigned problem of optimization requires decreasing a time of one calculation and (or) diminution of their amount.

For enhancement of computing efficiency in the algorithms of search optimization replacement of the original mathematical models (OMM) (grounded on laws, featuring the real physical phenomena and processes in the blade row *(CFD))* on their approximating dependences - the formal macromodels (FMM) is carried out. For creation of FMM performance criterion the methods of *DOE* theory are used.

Application of three-level plans of Box-Behnken [9] and Rechtschaffner saturated plans [10] at planning of numerical experiments with OMM allows receiving of FMM in the form of the full square-law polynomial providing precise enough description of the response function in the chosen hypercube:

$$P_2(x_1, x_2, \dots, x_n) = B_1 x_1{}^2 + B_2 x_2{}^2 + \dots +$$

$$+ B_n x_n{}^2 + B_{n+1} x_1 + B_{n+2} x_2 + \dots +$$

$$+ B_{2n} x_n + B_{2n+1} x_1 x_2 + B_{3n+2} x_2 x_3 + \dots +$$

$$+ B_{3n} x_m x_n + B_{3n+1} \qquad (3)$$

where $m = 1, 2, 3, \dots, n-1$ and $m \neq n$

Thus, as a result of the planned computation experiment processing the FMM performance criterion as functions of geometrical parameters is created.

Recently *DOE* theory methods are widely used in optimization algorithms [11, 12, 13]. For creation of FMM preliminary, with usage of *CFD,* the values of observation vector components in accordance with the plan of computing experiment are calculated. Each point of the plot represents an appropriate combination of design data. Processing of observations vectors according to *DOE* theory allows creating the FMM (By definition of coefficients B_i) target function usage of which enables to reduce required time of optimum solutions seeking by two orders (as rated test investigations have shown).

For our problem with three varied parameters FMM of target function $F(Y_h, Y_s, \Delta\beta_s)$ and restriction function $G(Y_h, Y_s, \Delta\beta_s)$ will look like following multinomials:

$$F(Y_h, Y_s, \Delta\beta_s) = B_1 Y_h^2 + B_2 Y_s^2 + B_3 \Delta\beta_s^2 + B_4 Y_h +$$

$$+ B_5 Y_s + B_6 \Delta\beta_s + B_7 Y_h Y_s +$$

$$+ B_8 Y_h \Delta\beta_s + B_9 Y_s \Delta\beta_s + B_{10} \qquad (4)$$

$$G(Y_h, Y_s, \Delta\beta_s) = C_1 Y_h^2 + C_2 Y_s^2 + C_3 \Delta\beta_s^2 + C_4 Y_h +$$

$$+ C_5 Y_s + C_6 \Delta\beta_s + C_7 Y_h Y_s +$$

$$+ C_8 Y_h \Delta\beta_s + C_9 Y_s \Delta\beta_s + C_{10} \qquad (5)$$

In the developed method at the solution of a set of turbine blade optimization problem the Monte-Carlo method with Sobol (LP$_\tau$) point sequences [14] are used. On fig. 4

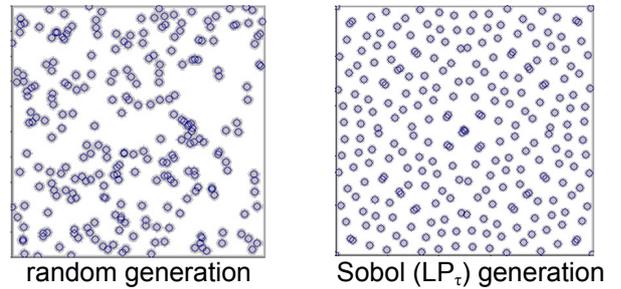| random generation | Sobol (LP$_\tau$) generation |

Figure 4. Kinds of points generation in square

examples random and Sobol points generation are brought. In figure it is visible, that at the same quantity of generated points Sobol sequences provides more uniform filling investigated area. Uniform filling with points of investigated area considerably increases efficiency of a Monte-Carlo method.

Optimum variants, which were gained as a result of optimization with usage FMM, in each case, were estimated with *CFD* usage. The values of target functions differed inappreciably, meeting the given demands of precision.

ALGORITHM OF OPTIMIZATION

Optimization process was conducted in correspondence with following algorithm:

1. The plan of computing experiment is created. In the given range of variation parameters, defining a stacking line, the points, in which computations will be carried out, are determined.

2. The blades matching of the plan points parameters are constructed and computation domain and grids are generated.

3. Meanings of target function for each combination of parameters are determined. For this purpose *CFD* computation and post-processing of results are carried out.

4. Coefficients of a full square-law polynomial of target function, and restriction function in the set range of varied parameters are determined. Further the minimal value $F(Y_h, Y_s, \Delta\beta_s)$ is determined provided that

$$G(Y_h, Y_s, \Delta\beta_s) - G_{init} < \varepsilon$$

5. The scope of varied parameters has been changed if necessary.

In case if the minimum of target function appears on the border of the range of variation parameters, the last is displaced aside of this boundary. If the minimum of target function are inside of the range, the last is restricted, and the point of target function minimum is accepted as a new centre of the range.

After changing of the range items 1-5 iterate until the minimal meaning of target function appears inside of a variation range, and its design values coincide with the given precision obtained on previous iteration.

6. Check *CFD* calculation of a flow in an optimum turbine blade rim is carried out for matching with the results gained on the last step.

RESULTS OF OPTIMIZATION INVESTIGATIONS

In accordance with the offered method and developed algorithm of optimization it has been carried out optimization research of a guide blade rim with the TS-1A profiles (Fig. 5) at different *a*/*l* (*a* - a throat of a blade
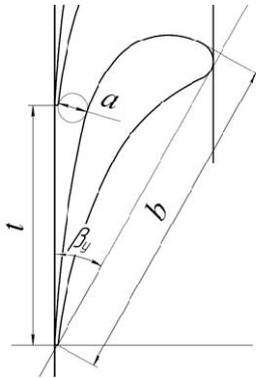

Figure 5. Blade profile TS-1A

passage, *l* – a blade height) for following flow conditions: **P*₁**=97759 Pa; **T*₁**=373.15 K; **P₂**=81861 Pa; **M₂**=0.48; **Re**=2×10⁶; working medium - air. The throat of a blade passage was practically constant. Its minor alteration is related to a small variation of a blade profile setting angle when in use of limitation of the mass flow rate of a working medium.

In the Table 2. the domain grid sizes for corresponding *a/l* are brought.

Table 2. Grid sizes for *a/l*

a/l	Grid sizes
0.44	166×70×40 (464800)
0.22	166×70×60 (697200)
0.16	166×70×90 (1045800)

Results of optimization computation within described method and algorithm permit confidently confirm the possibility decreasing of integral losses of a kinetic energy on an exit of a blade passage.

Quantity of losses decrease depends on the ratio *a/l*. The curves presented on Fig. 6 allow estimating a rational domain of application of the offered optimization method
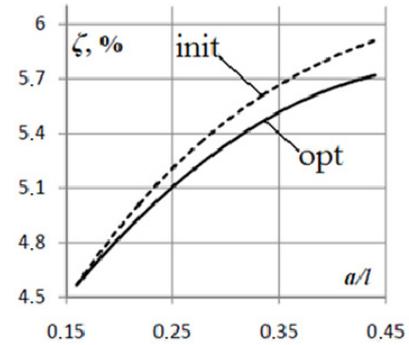

Figure 6. Total losses dependence from *a/l*

and algorithm. The shorter the turbine blade - the more significant gain. On Fig. 7 the optimized guide blade rim is shown at *a/l*=0.22.
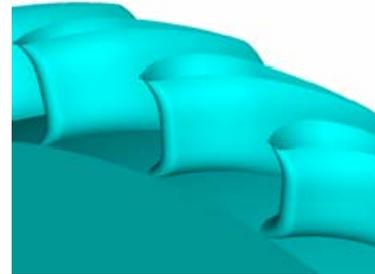

Figure 7. Optimized guide blade rim for *a/l*=0.22

Use in the developed algorithm of DOE theory methods has allowed to carry out such series of optimization researches, consisting all from nearby 100 numerical calculations (about 30 calculations on one optimization).

ANALYSIS OF THE REASONS OF AERODYNAMIC EFFICIENCY RISE

With the purpose of a physical explanation of the efficiency rise reasons of a turbine guide blade rim the detailed analysis of modify structure of a stream behind output edges in optimum variant in comparison with initial has been implemented.

As it is known, flow in a blade passage is accompanied by an secondary flow of a working medium on end surfaces of the channel as a result of a traversal pressure gradient [15] which, as it is shown in paper [16] and is visible on Fig. 8, reduces thickness of a boundary layer on a suction side of a blade in the field of their interacting. Last leads to improvement of a flow of a blade in these fields and to diminution of the losses related to a boundary layer on a
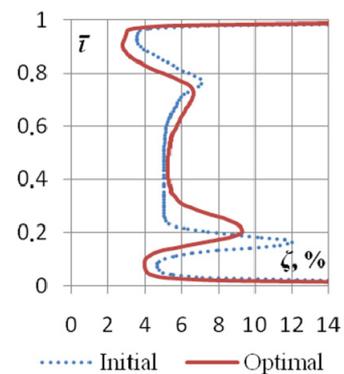

Figure 8. Total loss coefficient distribution along blade passage height

suction side of a blade. Applying the complex tangential

lean, we increment a part of these fields on blade height due to some shift of loss coefficient peaks to a flow core. Reorganization of a stream leads to diminution of losses peaks from secondary fluxions and scours them. At the same time it is accompanied by some magnification of losses in a flow core. However total integral losses appreciably decrease (Fig. 8, 9).

It is obvious, that there is a certain optimum standing of the specified fields on altitude of a blade passage which we and determined as a result of optimization. As a whole we may say that to expel a secondary traversal flow is not possible, but refining its interacting with a suction side of a blade, it is possible to increment aerodynamic efficiency of a turbine blade passage.

It is necessary to note, that application of the complex tangential lean leads to magnification of the real outlet angle of a stream near a root and peripherals, and, in turn, will lead to diminution of leakages in root and in radial gap. That could be additional provision of stage efficiency increasing as a result of optimization of the guide blade rim.
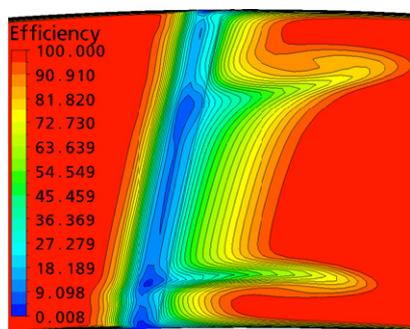
Initial blade passage
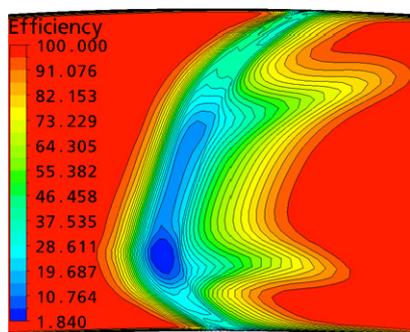
Optimized blade passage

Figure 9. Efficiency field on outlet from blade passage for *a/l*=0.22

CONCLUSION

The method and algorithm of optimization of guide blade rim of the axial-flow turbines has proposed and been developed, allowing its usage with various *CFD*-solvers. Utilization of the above mentioned method and algorithm for creation of high-performance stages of axial turbines with small D_m/l provide possibility to increase efficiency of high-pressure cylinders of powerful steam turbine appreciably.

ACKNOWLEDGMENT

REFERENCES

[1] Mohammad, A., Wahid, G., 2000, "A strategy for multi-point shape optimization of turbine stages in three-dimensional flow" *ASME TURBO EXPO 2009*, GT2009-59708.

[2] Rolf, D., Peter S., Dirk, B., 2000, "Multidisciplinary turbomachinery blade design optimization" *AIAA J. 2000*, AIAA-2000-0838.

[3] Damir, V., Zeljan, L., Igor, P., 2008, "A compact parameterization for shape optimization of aerofoils" *Proceedings of the World Congress on Engineering 2008*, Vol **I**, London, U.K.

[4] Fedorov, M. F., 1957, "Experimental research of mass flow and angular characteristics of nozzle type profile cascades TN-2: the Report about SIW", № **289**, Kharkov, Ukraine. (in Russian)

[5] Goncharenko, L. V., 1978 "Research of turbine stage with increased loading. Inflow effect on turbine stage work of a high pressure cylinder with D_m/l=13: the Report about SIW", № 77062748, Kharkov, Ukraine. (in Russian)

[6] Boiko, A. V., Govorushchenko, Yu. N., Burlaka, M. V., 2008, "Parametrical grid construction for turbine blades three-dimensional optimization", *Transactions of NTU "KhPI"*, Kharkov, № **6,** pp. 6-12. (in Russian)

[7] Boiko, A. V., Govorushchenko, Yu. N., Usaty, A. P., Burlaka, M. V., 2009, "Numerical research of complex tangential lean influence on the turbine guide blade rim characteristics", *Transactions of NTU "KhPI"*, Kharkov, № **3,** pp. 18-22. (in Russian)

[8] CGNS Project Group, 2007, "The CFD General Notation System Standard Interface Data Structures" Version 2.5.

[9] Box, E. P., Behnken, D. W., 1960, "Some new three-level design for the study of quantitative variables", *Technometrics*, 2, № **4**, pp. 455-475.

[10] Rechtschaffner, R. L., 1967, "Saturated fraction of 2n and 3n factorial design", *Technometrics*, № **9**, pp. 569-575.

[11] Kawagishi, H., Kudo, K., 2005, "Development of global optimization method for design of turbine stages", *ASME Turbo Expo 2005*, GT2005-68290.

[12] Prado, P., Panchenko, Y., Trepanier, J.-Y. and Tribes, C., 2005, "Preliminary multidisciplinary design optimization system: a software solution for early gas turbine conception", *ASME Turbo Expo 2005*, GT2005-69021.

[13] Philippe T. Lott, Nick J. Hills, John W. Chew, Timothy Scanlon and Shahrokh Shahpar "High pressure turbine stage endwall profile optimisation for performance and rim seal effectiveness", *ASME Turbo Expo* 2009, GT2009-59923, 13 p.

[14] Sobol, I. M., 1985, "The points which uniformly fill a multidimensional cube", *Mathematics, cybernetics series*, Znanie, Moscow, № **2**, pp. 32. (in Russian)

[15] Sieverding, C. H., 1985, "Resent progress in the understanding of basic aspects of secondary flows in turbine blade passages", *Transactions of the ASME, Journal of Engineering for Gas Turbines and Power*, Vol. **107**, pp. 248–257.

[16] Gukasova, E. A., Zhukovsky, M. I., Zysina-Molozhen, L. M., and other, 1961, "Aerodynamic improvement of steam and gas turbines blading", Gosenergoizdat, Moscow, Leningrad, pp. 167. (in Russian)