APPLICATION OF 3D FLOW SOLVER IN EDUCATION OF STUDENTS

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Abstract: The development of 3D numerical methods enables the estimation of flow parameters in any section of the channels and in this way the complex phenomenon of generation of losses can be investigated. Application of 3D solver helps in better understanding of flow behaviour in turbine stages, while basing on the results of calculations of stages of different geometries, it is possible to show the effect of different design parameters on the turbine stage output and its efficiency. The paper presents the examples of application of modern computer programs for teaching turbomachinery problems, for research flows in turbine stages and for solving design tasks. Some examples of students' projects are also included.

Keywords: Computational Fluid Dynamics, education

1. Introduction

The CFD methods are nowadays used for calculations and designing flow parts of turbines and compressors in industrial practice. Thus aiming at meeting these standards and the expectations of turbomachinery companies the modern flow solvers are introduced to the standard curriculum of higher technical education, which is followed by more advanced investigations and algorithms developed during postgraduate studies. In the Turbine Propulsion Department of the Faculty of Ocean Engineering and Shipbuilding Technology (Technical University of Gdansk), for the last two years students have had the opportunity to perform calculations, to design and even to investigate some problems by means of the 3D flow solver FlowER [1, 2], which enables the determination of parameters of compressible viscous flows through multi-stage machinery. The code draws on:

- a set of thin-layer Reynolds-averaged Navier-Stokes equations,
- a modified algebraic Baldwin-Lomax model of turbulence,
- perfect gas equations,
- an H-type calculation grid,
- a high resolution ENO scheme,

- the δ-form implicit operator of Beam and Warming.

The application of 3D solvers is preceded by seminars and classes on:

- mathematical models of 1-, 2- and 3-dimensional flows in turbine or compressor stages,
- models of turbulence,
- numerical methods for solving 3D differential equations (types of grids, numerical algorithms).

After gaining this theoretical background the students begin learning the solver, defining a set of the fluid thermodynamical parameters, practicing the creation of the turbine stage geometry with the appropriate numerical grid construction and carrying out some calculations. This is followed by the most interesting and important part of scientific investigation – analysis, in which the distributions of flow parameters like pressure, velocity vectors, entropy, Mach numbers, density and loss coefficients are examined and discussed. It helps in better understanding of flow behaviour in turbine cascades, interaction between nozzle and rotor cascades, and interaction between the main flow and the streams of leakage. Moreover, basing on the results of calculations of stages of different geometries, it is possible to show the effect of such design parameters as velocity ratio, stage diameter, blade height, profile chord, stagger angle (cascade outlet angle and cascade pitch), pitch-to-chord ratio (number of blades) or types of profile on the turbine stage output and its efficiency. This analysis is usually performed during the students' industrial practice or is included in the syllabus of the students' research workshop. Similar problems may also concern the theme of the final thesis and in some of the most interesting cases it may be continued during postgraduate studies. This model of assimilation of modern computer programs for teaching turbomachinery problems, for investigating flows in turbine stages and for solving design tasks was developed at the Technical University of Gdansk thanks to the cooperation between the Turbine Department of the University with the Institute of Fluid Flow Machinery of Polish Academy of Sciences and with the concern ABB Ltd in Elblag (now Alstom Power Ltd). ABB Ltd enabled the industrial practice during which students performed certain tasks concerning the design of the flow part of a steam turbine. Another group of students, during a research workshop organised in the Institute of Fluid Flow Machinery, worked on elaboration of characteristics of nozzle and blade cascades, including efficiency, mass flow coefficients and the nozzle exit angles.

2. Examples of students' projects

A. During the summer research workshop students took part in calculations of variants of steam turbine stages of the impulse type. Different cascade parameters such as profile chords, nozzle heights, stagger angles, cascade pitches and inlet flow angles were taken into account. For each variant the students defined a set of flow data, created the stage geometry with an appropriate grid and finally carried out the calculations. They obtained the results which contribute to the elaboration of a set of cascade characteristics. Special attention was paid to the estimation of the cascade efficiency, the cascade flow coefficients and the cascade exit angles [3–6].

The calculations were carried out for cascades typical of impulse turbine stages:

- a nozzle cascade with a Mach number Ma = 0.4–0.9, nozzle inlet angle $\alpha_0 \approx 90^\circ$ and outlet angle $\alpha_1 \approx 15^\circ$,
- a rotor blade cascade with a Mach number Ma = 0.3 − 0.8, blade inlet angle $\beta_1 \approx 30^\circ$ and outlet angle $\beta_2 \approx 22^\circ$.

Different values of profile chords b, nozzle heights l, diameters D, stagger angles β, cascade pitch-to-chord ratios t/b (different blade numbers), incidence angles and Mach numbers were taken into account. The performed calculations enabled the investigation of the distribution of flow parameters, such as velocity vectors, entropy creation, losses of kinetic energy, pressure, density. Some of the examples are presented in Figures 1, 2 and 3.

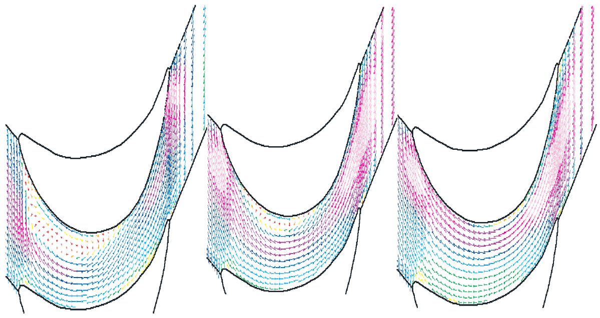

Figure 1. Velocity vectors of the flow in a rotor cascade

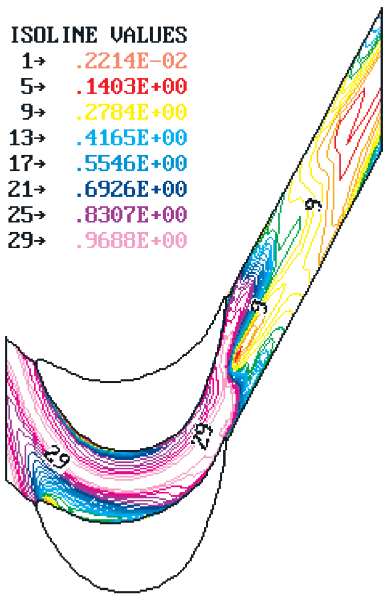

Figure 2. Example of distribution of kinetic energy losses in a blade cascade

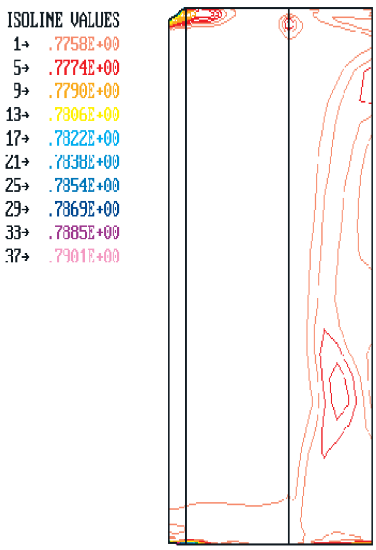

Figure 3. Example of entropy creation (meridional section of blade cascade)

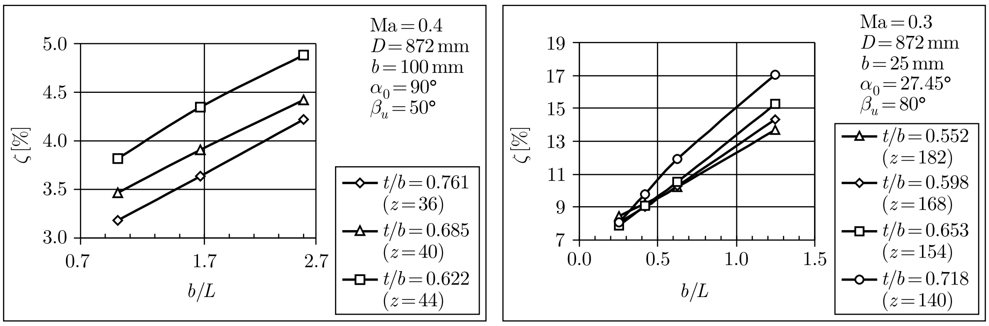

Figure 4. Cascade loss coefficient for different pitch-to-chord ratios t/b as a function of chord-to-height ratio b/l for the nozzle (left) and rotor blade (right)

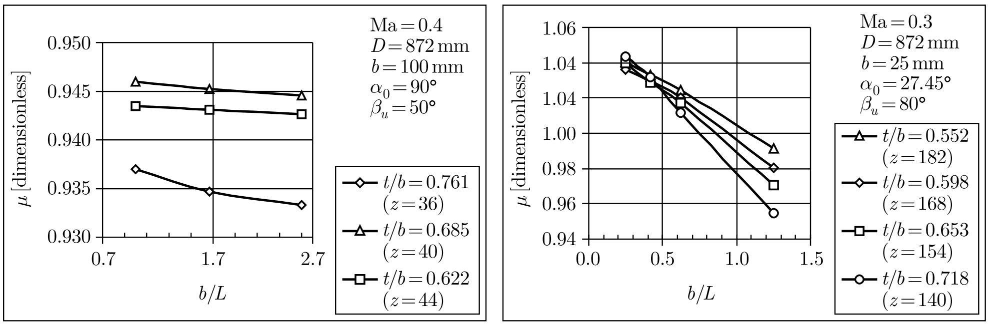

Figure 5. Cascade flow mass coefficient for different pitch-to-chord ratios t/b as a function of chord-to-height ratio b/l for the nozzle (left) and rotor blade (right)

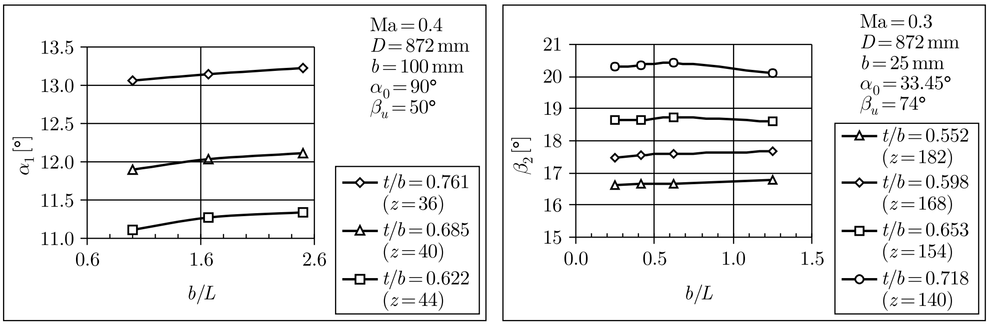

Figure 6. Cascade exit angle for different pitch-to-chord ratios t/b as a function of chord-to-height ratio b/l for the nozzle (left) and rotor blade (right)

The calculations were performed for hundreds of different cascade geometries and flow parameters. Basing on the obtained results, the characteristics of cascade efficiency, mass flow coefficient, and exit angle were elaborated in the form of:

$$\eta = \eta(\beta, t/b, b/l, l/D, \alpha, \mathrm{Ma}),$$
$$\mu = \mu(\beta, t/b, b/l, l/D, \alpha, \mathrm{Ma}),$$
$$\alpha = \alpha(\beta, t/b, b/l, l/D, \alpha, \mathrm{Ma}),$$

where the flow coefficient $\mu = G/G_i$ is defined as the ratio of the cascade mass flow rate G to the cascade mass flow rate G_i in the case of isentropic expansion. The

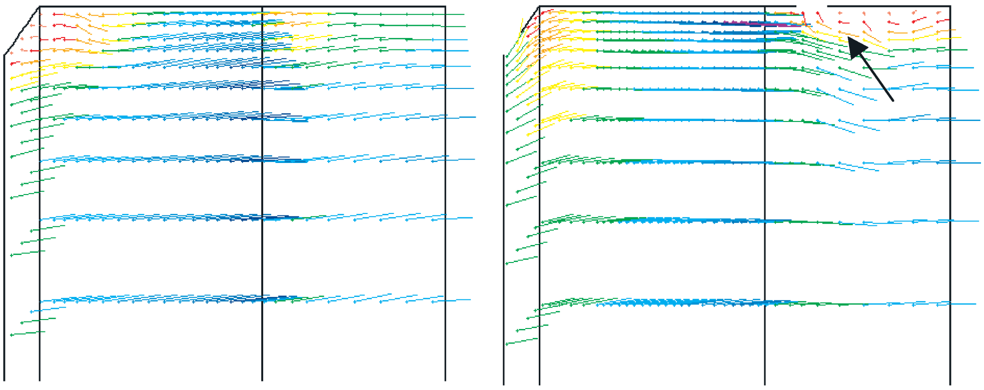

Figure 7. Velocity vectors in the middle of the flow passage in the meridional plane at the tip of the blade without leakage (on the left) and with leakage (on the right)

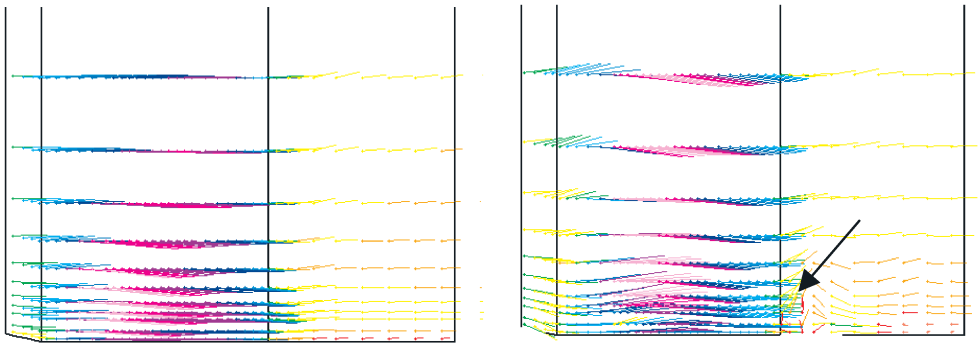

Figure 8. Velocity vectors in the middle of the flow passage in the meridional plane at the hub of the blade without leakage (on the left) and with leakage (on the right)

characteristics were included in a technical report, partially described and discussed in papers [3–6]. The paper presents some of the examples. Figures 4, 5 and 6 show cascade losses, mass flow coefficients and cascade exit angles for nozzle and rotor blade profiles, respectively.

The obtained computational results proved the effect of profile chords, blade heights, stagger angles, and pitches on the performance of stator and rotor cascades. They gave a vast collection of distributions of velocity, pressure, entropy and energy losses in particular areas of cascade passages, which are of great help in the interpretation of the influence of different geometry and flow parameters on turbine stage performance.

B. Very interesting problems were investigated during the preparation of MSc Thesis [7]. Computations of 3D flows through the steam turbine stages were performed with FLOWER solver taking into account both the cascade losses and the leakage losses. For each set of given parameters calculations were performed twice – with and without leakages. The interaction between leakage streams and the main stage flow was taken into account in the calculations. The analysis of the 3D steam flow in a turbine stage of the impulse type, with a prismatic nozzle and blade profiles, was carried out basing on the results of numerical calculations. The comparison of the obtained results leads to certain conclusions concerning the influence of the leakage streams on the main flow and on the energy losses. Figure 7 and 8 present the influence of the leakage on velocity vectors at the blade tip and the blade hub respectively, while Figure 9 presents an example of distribution of losses along the blade height. Similar results were obtained for stages with different blade geometry and different mass flow rate. Basing on these results it may be stated that the leakage affects the velocity vectors' distribution in the main flow and as a result it influences the endwall losses, secondary losses, profile losses and even exit kinetic energy losses.

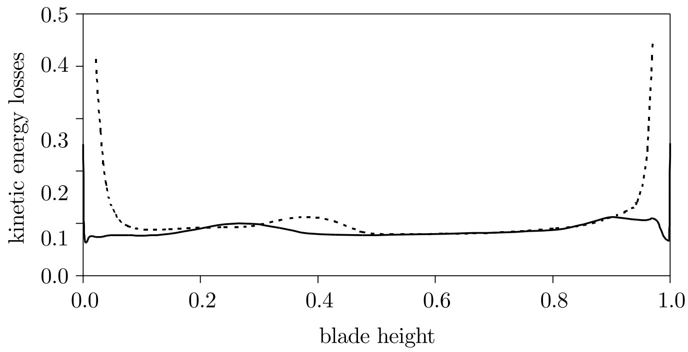

Figure 9. Energy losses distribution: dashed line – with leakage, and solid line – without leakage

The influence of the angle, ε, at which leakage flow is injected into the main stream, on losses was also investigated by means of the 3D solver FlowER. The value of losses depends not only on the leakage flow rate but also on the leakage flow configuration. The tip clearance leakage injected behind the blade leads to some disturbances of the main flow: changes the directions of velocity vectors, causes vortices, locally reduces total pressure and affects kinetic energy losses. The scheme of the leakage flow through the blade tip clearance is shown in Figure 10. Behind the blade the leakage flow interacts with the main channel flow and this interaction causes some additional losses. The velocity v of the leakage stream in this region is represented by its radial (v_r), axial (v_a) and circumferential (v_u) components. The angle ε (Figure 10) was assumed as a varying parameter. The lowest value of the angle ε is equal to the nozzle outlet angle, while the highest one exceeds the value of the absolute stage outlet angle.

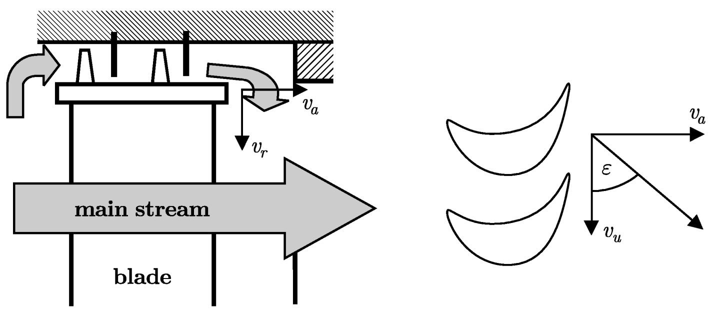

Figure 10. Definition of the angle at which leakage is injected into the main stream

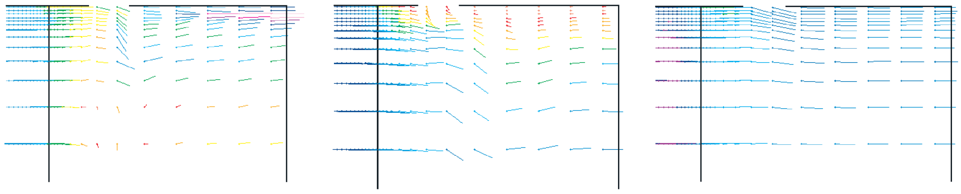

Figure 11. The influence of the angle ε on velocity vectors in the meridional plane (in the middle of the passage); $\varepsilon = 11.5^{\circ}$ (left), $\varepsilon = 60^{\circ}$ (middle), $\varepsilon = 106.6^{\circ}$ (right)

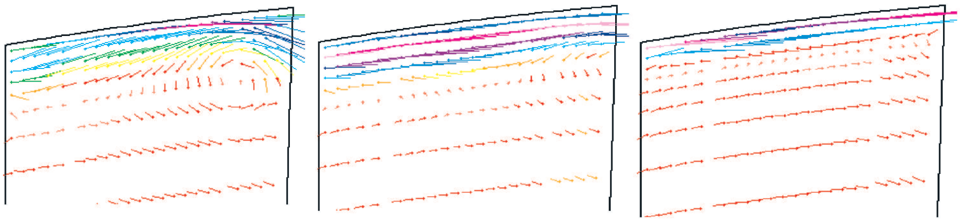

Figure 12. Velocity vectors in the circumferential direction (at 72% of the axial chord downstream from the trailing edge); $\varepsilon = 11.5^{\circ}$ (left), $\varepsilon = 60^{\circ}$ (middle), $\varepsilon = 106.6^{\circ}$ (right)

The influence of the angle ε on the velocity vectors of the blade cascade flow is presented in Figures 11 and 12. Performed calculations have proved that the energy losses caused by the leakage flows depend not only on the value of the leakage flow rate but also on the velocity vector of the leakage flow. The leakage stream influences the cascade losses and also the average value of the exit kinetic energy. For the blade seals of the labyrinth type the direction of the flow in the tip clearance corresponds more or less to the nozzle outlet angle, while the main stream flows out from the blade cascade at a much greater absolute outlet angle. In the analysed variants of steam turbine stages the proper configuration of the leakage stream had blade losses reduced by about 5% and exit kinetic energy reduced by about 1.5%. In this way the overall stage efficiency increased by about 2%.

The proper configuration of the leakage stream velocity vectors may reduce the overall stage losses and may increase total stage efficiency even by 2%. The leakage stream outlet angle ε ought to be equal to about the absolute stage exit angle. This is the main suggestion, which should be considered when designing blade shrouds of the new type.

C. 3D calculations of a compressible viscous flow through turbine stages are nowadays treated as state-of-the-art in turbine design practice. But this designing process of turbine blades or whole turbine stages, especially based on the 3D Navier-Stokes solver, takes a lot of time. Development of artificial intelligence (AI) can shorten this time. Some AI applications have already been used in industry *i.e.* for optimising 3D blade profiles by maximizing efficiency with some mechanical constraints. Connecting AI with the concept of function approximation seems to be very efficient for turbomachinery design process. The steam turbine design method using neural networks and genetic algorithms was proposed as a subject for PhD studies. The first approach to that concept was described in conference paper [8]. Similarly to the blade optimisation by means of a function approximation concept based on an artificial neural network and genetic algorithm [9], the design method for the turbine stage optimisation has

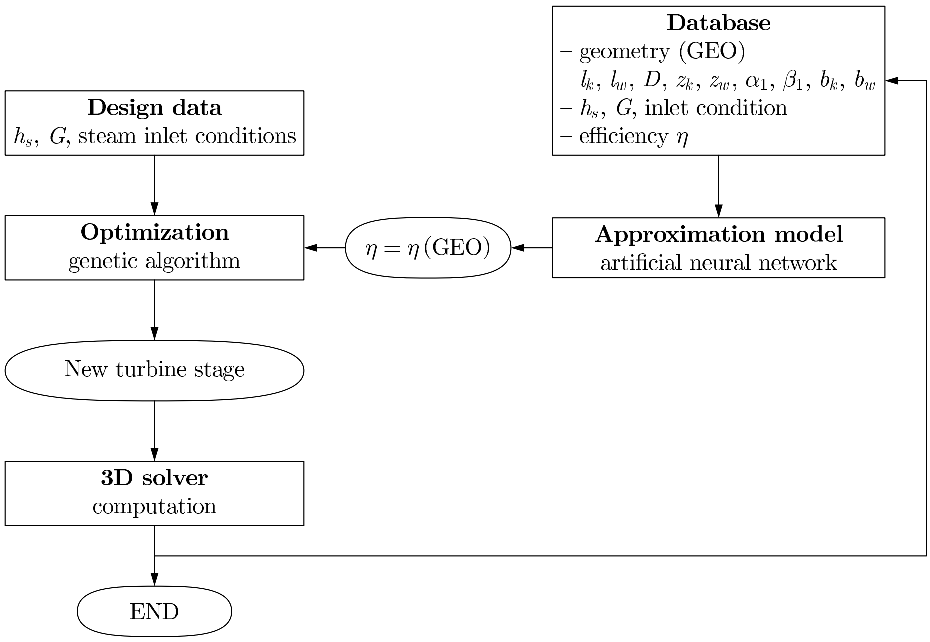

Figure 13. Design algorithm

been put forward. The general scheme of the design concept is presented in Figure 13. The database consists of samples taken from 3D computation (mainly), experiments and previous industrial experience. The calculations are performed using the solver FlowER, which enables the determination of parameters of compressible viscous flows through multi-stage machinery.

A genetic algorithm consists of the 5 following steps:

1. Creation of an initial population. The initial population (here a set of stages) is generated by randomly creating individuals (turbine stages). Such parameters as D, z_k, z_w, α_1, β_1, b_k, b_w are chosen at random and l_k, l_w are calculated as a function of these parameters and the design data.
2. Calculation of the objective function (efficiency) for all the individuals in this population. The objective function is used to measure the fitness of an individual and it is evaluated by a neural network.
3. The selection. In this step, the selection operator chooses two individuals from the population. The selection probability is not the same for all individuals. It is proportional to the fitness of an individual. In this step, the parents chosen during the selection generate the new population by means of crossover and mutation.
4. The offspring create a new generation, which becomes the initial population for the next iteration of the genetic algorithm. The process is repeated until the termination criterion is reached.
5. When the optimum stage is reached, the flow in the stage is calculated by a 3D solver in order to obtain the exact value of efficiency and other performance. New samples can be added to the database.

Work on the stage design algorithm is in progress and it is expected to simplify the design and accelerate the present method.

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References

[1] Yershov S V and Rusanov A V 1996 *The Application Package FLOWER for the Calculation of 3D Viscous Flows through Multistage Turbomachinery*, Certificate of Ukrainian State Agency of Copyright and Related Rights, Kiev, Ukraine, 19 February

[2] Yershov S V, Rusanov A V, Gardzilewicz A, Lampart P and Świrydczuk J 1998 *TASK Quart.* **2** (2) 319

[3] Gardzilewicz A, Lampart P, Świrydczuk J and Kosowski K 2000 *Cieplne Maszyny Przepływowe* **117** (1) 179 (in Polish)

[4] Gardzilewicz A, Świrydczuk J, Lampart P, Kwidziński R and Kosowski K 2000 *Cieplne Maszyny Przepływowe* **117** (1) 187 (in Polish)

[5] Gardzilewicz A, Lampart P, Świrydczuk J and Kosowski K 2000 *2nd Int. Sci. Symp. on Technical, Economical and Environmental Aspects of Combined Cycle Power Plants, COMPOWER 2000*, Gdansk, Poland, pp. 121–126

[6] Gardzilewicz A, Lampart P, Świrydczuk J and Kosowski K 2000 *2nd Int. Sci. Symp. on Technical, Economical and Environmental Aspects of Combined Cycle Power Plants, COMPOWER 2000*, Gdansk, Poland, pp. 127–132

[7] Siamion J 2000 *The Theoretical Investigations of the Influence of the Leakage Losses on the Turbine Stage Efficiency*, MSc Thesis, Technical University of Gdansk, Poland (in Polish)

[8] Kosowski K and Siamion J 2001 *5th Conference on Algorithms and Global Optimisation*, Jastrzebia Gora, Poland, pp. 130–134 (in Polish)

[9] Pierret S 1999 *Designing Turbomachinery Blades by Means of the Function Approximation Concept Based on Artifical Neural Network, Genetic Algorithm and the Navier-Stokes Equations*, PhD Thesis, von Karman Institute, Belgium