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113

Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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Aims and Scope

Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 119-128

TADEUSZ CHMIELNIAK*, HENRYK ŁUKOWICZ, WŁODZIMIERZ WRÓBLEWSKI and SŁAWOMIR DYKAS

Numerical prediction of losses in the low pressure last stage blade

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Abstract

The aim of presented research is to estimate the losses in the flow of steam through the rotor of last stage LP steam turbine. In this case two types of losses may take place, namely aerodynamic (profile, secondary flow, leakage) and thermodynamic (due to the heat addition caused by condensation). In the paper three different calculation models have been compared. The first one is the streamline curvature method (SCM), used on the meridional plane with correlations of losses, and the other are based on the Reynolds averaged Navier-Stokes governing equations. The N-S equations for the 3D steam flow are solved using two models for the liquid phase. The first one is an equilibrium dry/wet steam model and the second one is the nonequillibrium model. In this case, the governing equations are coupled with the system of partial differential equations describing the liquid phase. The real gas local equation of state is used in calculation of the water-steam properties and thermodynamic functions. The homogeneous nucleation processes in the water steam are modeled using the classical nucleation theory. Flow in the considered case has strong 3-D character and real gas effects are significant, which causes significant losses in the last stages. The results of calculations of the wet steam flow are discussed and compared.

Keywords: Steam turbines; Flow modeling; Numerical methods; Wet steam; Losses

Nomenclature

h – enthalpy drop, kJ/kg
s – entropy, kJ/(kg K)
w – relative velocity, m/s
T – temperature, K
Δ – quantity increase

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Subscripts:

1 – inlet
2 – outlet
s – isentropic quantity
R – rotor

1 Introduction

The development of numerical methods in fluid mechanics as well as th constant growth of information concerning the dissipation of energy in flow systems, which are characteristic for thermal fluid-flow machines, form the basis fo more and more reliable methods of calculations and algorithms of aerodynami optimisation. The process consists in the resignation of simplifications in th mathematical description of the phenomena taking place, the possibilities of taking into account the actual geometry, a more detailed description of the propertie of working media, and the application of advanced procedures in the analysis an processing of calculation results.

In the last stages of the low-pressure steam turbine the losses are difficult t estimate. The main reasons are: relatively high change of parameters along th blade height, transonic and supersonic flows and two-phase character of the flow In the last stages two types of losses should be taken into account: aerodynami losses caused by the interaction between fluid and wall boundaries and thermodynamic losses produced during the phase change.
The prediction of losses is the main aim of many works, either done experimentally [1-3] or numerically [4, 5]. In the most numerical models the losses in th steam turbines are calculated using the ideal gas model. It is a justified simplification in cases when the stages operate on the superheated steam [2, 6]. In case where the low-pressure stages are taking into account two-phase character th losses could play an important role. Especially it should be possible to model th entropy production in the flow when the phase change takes place.

To estimate the losses different algorithms have been used. The first one i based on the streamline curvature method. The results of calculations depen on the assumed relations describing the losses of energy. From many availab relations, permitting the determination of losses, the correlations suggested in [7 have been adopted. The main reason for such a choice was the extensive experimental material as well as the closed system of relations, which make it possibl to calculate all kinds of losses.

The progress in the numerical modelling permits to determine more accurately the 3D structure of the flow parameters. Other algorithms used in calculations are based on the finite volume method. The commercial code TascFlow an the in-house code were used. The in-house code is able to take into consideration the thermodynamic losses caused by condensation (nonequilibrium model), but the TascFlow code uses the equilibrium dry/wet steam model.

Numerical investigations are performed on geometry of the two rotors of LP part of the large output steam turbine.

2 Numerical analysis

2.1 Streamline Curvature Method (SCM)

The classical Streamline Curvature Method is used to simulate the flow in the meridional plane. In this method the real gas equation of state for the water steam is applied. Detailed description of the method could be found in [8]. In the conservation equations, the energy dissipation is included using empirical formulas. The losses are divided into profile, boundary and additional losses. Empirical correlations for this kind of losses are proposed by i.e. Aleksejeva, Craig-Cox and can be found in [7, 9]. The input data for the calculation of the respective components consist in the geometry of the blade system (of the blading) and the distribution of parameters at the inlet and outlet of the blade rows.

An important problem is the determination of distribution of boundary losses along the blade height. It is difficult to estimate various ways of distribution suggested in literature, mainly due to the scarcity of experimental information. Calculation methods have been tested against the results of measurements performed on the stages of a steam turbine [10]. Obtained results of calculations indicate that the method of distribution of the losses along the height of the blade, suggested in [7], guarantees a qualitative agreement with the experiment. Quantitative deviations are particularly distinct in the case of the angle of outflow from the stage. Similar results are obtained making use of the Traupel's recommendation [11].

2.2 Commercial code TascFlow

In this case the fluid flow field is determined using the commercial code TascFlow [12]. It is a widely used code in the area of turbomachinery applications. TascFlow is based on the averaged Navier-Stokes equations employing the finite volume method (FVM) with an implicit, multiblock algorithm. The solution strategy is based on the Algebraic Multigrid method. TascFlow has many possibilities of turbulence modelling. In this case, the turbulence was modelled using the Menter's SST *(Shear-Stress-Transport) model [13, 14]. It is a combination* of $k-\omega$ and $k-\varepsilon$ model: $k-\omega$ model near the surface and $k-\varepsilon$ model for the free shear flows (ε equation is transformed to ω). Mixing is performed automatically on the basis of the solution and the distance from the surface. The code combined with the SST limiter offers optimal boundary layer simulation capabilities [15]. The real gas flow in this case was modelled using the approximation of the water-steam tables. In this calculation the equilibrium in the two-phase flow was assumed.

2.3 Finite Volume Method (FVM)

The third round of calculations was performed using our own codes. The numerical simulation is based on the time dependent 3-D Reynolds averaged Navier-Stokes equations, which are coupled with a two-equation turbulence model ($k-\omega$ SST model) and additional mass conservation equations for the liquid phase (two for homogeneous and one for heterogeneous condensation). The set of governing equations is closed by a real gas equation of state. The condensation phenomena are modelled based on the classical nucleation theory of Volmer, Frenkel and Zeldovich, which is well suited for modelling of technical flows [16, 17]. The Gyarmathy's droplet growth equation is used. The system of governing equations is discretized on a multi-block structured grid using the finite-volume method and integrated in time using an explicit Runge-Kutta method. An upwind scheme is used with the Riemann solver proposed by Godunov. The MUSCL technique is implemented to approach the TVD scheme with the flux limiter to avoid oscillations. Description of the method could be found in [18, 19].

3 Calculation results

The numerical calculations are applied to the rotor geometry of the last and penultimate stages of the LP part of steam turbine. The gap between the rotor tip and casing were not modelled and therefore leakage losses were not taken into account. For the last stage two different operating conditions, relatively far from the nominal load, were considered. In the case of penultimate rotor the nominal load was calculated.

Computational domain was discretized using the structural Multiblock grid in which the O-type grid near the blade is embedded within a C-type grid and in the inlet and outlet domain the H-type grid is used. The construction of the O-type grid is done in such a way as to ensure that the distance of any grid points adjacent to a blade wall, measured in wall units y^+, is in the main calculations less then two. Numerical grid for the last rotor consists of about 268000 points (Fig. 1) and for the penultimate rotor about 170000 points, respectively.

An example of the cascade parameters distribution in the rotor channel of the last stage is presented in Fig. 2.

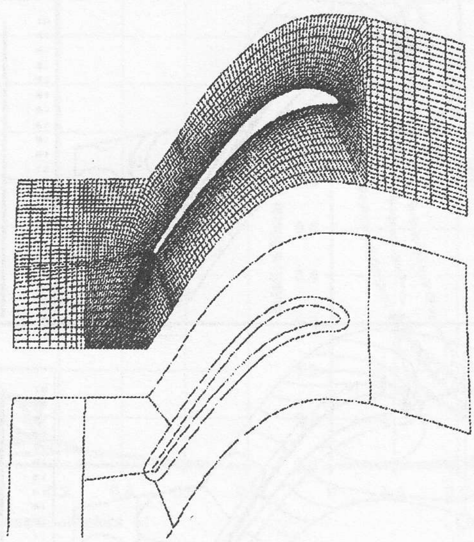

Figure 1. Last stage rotor discretisation using Multiblock grid (middle section).

The cascade loss coefficient was calculated from the formula:

$$\zeta = \frac{T_2 \Delta s}{\frac{1}{2} w_{2s}^2} = \frac{T_2 \Delta s}{h_{sR} + \frac{1}{2} w_1^2} \quad (1)$$

It is determined as the spanwise distribution from the pitch-averaged flow parameters. In the streamline curvature method it is a basic assumption that parameters are treated as circumferentially averaged. In the 3D calculations the quantities used in this procedure have to be pitch-averaged. The averaging procedure calculates the mass-averaged values for enthalpy and entropy at the inlet and outlet as well as algebraic-averaged values for temperature and velocity. It is assumed that the streamlines in the meridional plane are close to the grid lines.

Figure 3a shows the comparison of the loss coefficients calculated using different calculation methods and flow models for the operating conditions 140 MW and p_{out} = 2.7 kPa. In this case loss coefficient distributions along the blade span are relatively close to each other. Discrepancies between streamline curvature method and finite volume method with wet steam models are greater in the root section and tip section. The results are in a relatively good agreement between SCM and FVM calculations and adiabatic flow model. Calculation results with wet steam models fall very close in the middle and tip sections. In the root section only the qualitative agreement is observed.

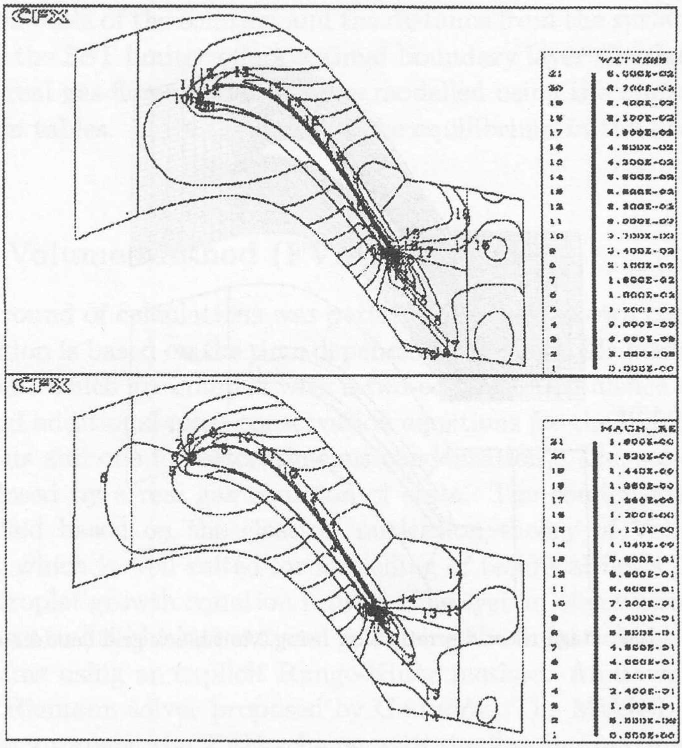

Figure 2. Wetness fraction (a) and Mach number (b) distribution in the last stage rotor (TascFlow, middle section).

In the case of operating conditions 140 MW and $p_{out} = 3.7$ kPa distributions of the loss coefficient are shown in Fig. 3.b. It is difficult to explain that the FVM calculations give greater loss coefficient than in the previous case but in the case of SCM calculations the opposite effect was present. In this case the discrepancies between the FVM with wet steam model and SCM calculations are significant. A good agreement between SCM calculations and FVM with adiabatic (dry steam) flow model is observed. Loss distributions are very close in the root section but in the tip section differences are considerable.

In the case of the penultimate rotor which (Fig. 4) relatively good qualitative agreement is observed up to the 25% of the blade span. The losses discrepancies between SCM and FVM calculations are about 4 percent points. Near the tip section loss distributions are very close to each other. In the root section differences are significant. In this section the participation of the boundary losses is observed to the 20% of the blade span in all models. The finite volume methods

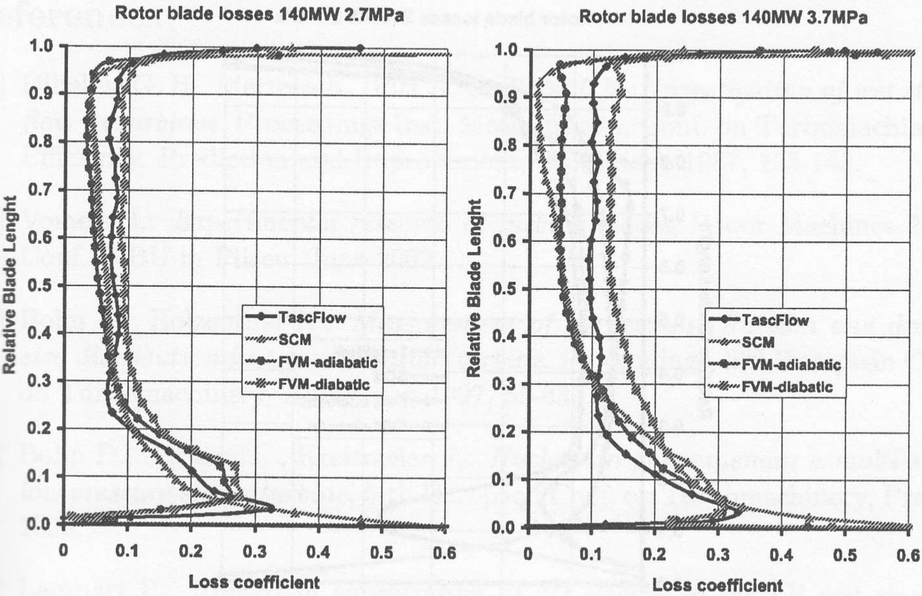

Figure 3. Loss coefficients comparison for different operating conditions (last stage).

with two phase flow models gave very similar losses distributions.

In the loss distributions obtained from the FVM calculations some not physical effects are present. Curves in the root section show losses reduction with different gradients even approaching to the negative values. The reasons might be the circumferential averaging procedure, lack of the streamline and grid line agreement especially in the near wall domains with strong gradients.

It will be strong recommended to perform validation of these calculation methods on the experimental data of the real steam turbine stage operated on wet steam.

4 Conclusions

The different methods of fluid flow calculation are used to estimate loss coefficient in the rotor. Presented methods used different dry/wet steam models. The finite volume calculation methods were compared with the streamline curvature method with empirical correlations for the loss coefficients. The in-house code to calculate the flow phenomena was tested with the commercial finite volume code TascFlow. In the considered problems all finite volume methods were stable, and showed relatively good stability and convergence. This capability of the in-house code allows calculating the flow field with condensation in the wide range of op-

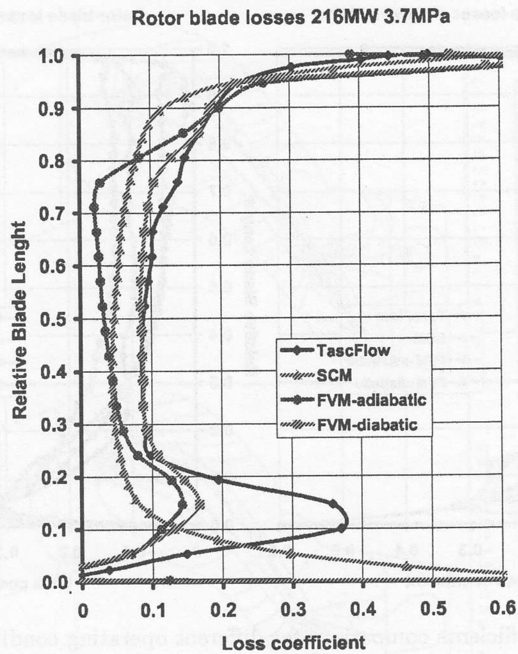

Figure 4. Comaprison of loss coefficients for different operating conditions (penultimate stage).

erating parameters. In the finite volume method almost the same turbulence modelling was used.

Computational results of the two-phase flow modelling through a turbine cascade were presented. Different flow conditions will be considered. In all cases the differences in loss coefficient distributions between streamline curvature method and finite volume methods were observed. The loss coefficient distributions are qualitative very similar, but quantitative discrepancies were observed. The sources of these discrepancies are not easy to explain. It is not possible to evaluate which method is closer to the real physics. The results of calculation were obtained as the first results of our work, which is concerned with modelling of the losses in the two-phase flow. The results show that the more precise analysis should be done and influence of some chosen parameters on the solution should be investigated.

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