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THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Modular algorithm for the flow analysis in heat turbines

The paper deals with a modular algorithm for the solution of practical problems turning up in the course of the construction and modernization of heat turbines. The essence of such algorithm is the utilization of various flow models while analysing specific problems. Selected results of calculations have been presented.

1. Introduction

Development of numerical methods in fluid mechanics as well as the constant growth of information concerning the dissipation of energy in flow systems which are characteristic for thermal fluid-flow machines form the basis for more and more reliable methods of calculations and algorithms of aerodynamic optimization. The process consists of the resignation from the simplifications in the mathematical description of the occurring phenomena. The actual geometry, a more detailed description of the properties of the working media, and the application of advanced procedures in the analysis and post-processing of the calculation results can be taken into account.

The process of solving some given flow problem usually comprises the elements listed in the Table 1 [1].

Each stage is momentous for the final result. The fundamental moment, however, is the assignment of a mathematical model to the investigated phenomenon. The flow in heat turbines belongs to the family of internal flows. In order to model them, various steps of physical and mathematical simplifications are applied [1, 3]. The most general model comprises a complete set of conservation laws (equation of continuity, Navier-Stokes equations and the energy equation), initial and boundary conditions as well as equations describing the properties of the working media. In the first stage we pass from the Navier-Stokes equations

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Table 1.

Basic problem	Main sub-problems	Result
Discussion of the physics of the phenomenon	Physical and geometrical simplifications – selection of the flow domain	Mathematical model
Mathematical model	Choice of the discretisation method of the flow domain	Grid geeneration
	Discretisation of integral and differential equations of fluid dynamics	Difference equations for internal domain
Discretisation of the boundary conditions	Numerical implementation of the boundary conditions	Boundary schemes
Interior and boundary differential equations	Methods of solution	Solution
Discussion concerning the solution	Assesment of the accuracy and sensitivity to changes of the chosen parameters etc.	Conclusions

to the Reynolds equations averaged in time and locally in space, which require the introduction of turbulent stresses. By solving them we get information about the field of thermodynamic and kinematic parameters, the value of energy dissipation and the efficiency of the conversion of energy in the considered flow. The procedure of calculation developed so far make it possible to solve a wide range of boundary problems based on the considered mathematical flow model, but no agreement has been reached as yet to the practical usability of the applied assumptions and models of turbulence. Moreover, the costs of solutions are still considerable in the three dimensional cases. At the Institute of Power Machinery, Technical University of Silesia, investigations have been carried out, resulting in the elaboration of a procedure for two-dimensional problems. The designers and researchers have also at their disposal a well-developed group of methods concerning compressible inviscid flows (algorithms for the solution of steady and unsteady Euler equations), both for the respective channels and the whole stages of flow machines (e.g. [1-4]). As calculations consume much time and are rather expensive, it is not always possible to apply the aforesaid models in detailed parametrical and optimising calculations. Therefore the performance characteristics across the whole range of loading are determined by means of other methods, mainly those approximating the flow based on solutions of cascade problems and in the meridional cross-section, assuming that the losses of energy are distributed over the respective elements of the flow machine.

The paper presents an outline of a general algorithm for aerodynamic calculations of the flow system of heat turbines (mainly steam turbines), assuming the application of various mathematical models of the flow, depending on the given considered problems. The application of the elaborated detailed algorithms has been illustrated by the results of calculations concerning various flow problems.

2. General structure of the algorithm for the flow calculations in the heat turbine stages

In the Institute of Power Machinery, Technical University of Silesia, an algorithm has been developed for the analysis of the flow in the stages of the turbine, comprising – among others – the following modules:

- Module 0 – determination of the expansion line (the through-flow method connected with the set of the equations for losses calculation in the flow).
- Module 1 – solution of flow equations with applied model of energy losses distribution in the meridional plane,
- Module 2 – solution of Euler non-stationary equations (for any given geometry and any range of Mach numbers),
- Module 3 – solution of averaged Navier-Stokes equations (Reynolds equations) in two dimensions, making use of Baldwin-Lomax's or $k - \varepsilon$ hypothesis.

The application of these algorithms makes it possible to solve various flow problems. An example of the composition of modules is to be seen in Fig. 1. In many cases much practical information concerning for instance the determination of an exact expansion line, the thermodynamic and kinetic parameters in the respective cross-sections of the flow part at various loads as well as the assessment of attempts of modernisation (pressure changes in the condenser, changes of the stage geometry etc.) are expected. In those cases usually merely the application of the algorithms contained in module 0 and 1 is needed for the whole flow system or a group of stages. The application of these modules is generally also required - due to the determination of actual boundary conditions. More detailed information concerning the work of the given stage must be obtained by solving Euler equation (for the whole stage, in steady or unsteady formulation, cross-sections 1-2 in Fig. 1) or by solving Navier-Stokes equation in the case of a cascade problem (cross-sections a-b or a-b-c in Fig. 1). Other configurations of applying these algorithms within the range of the modules 0-3 are, of course possible, too.

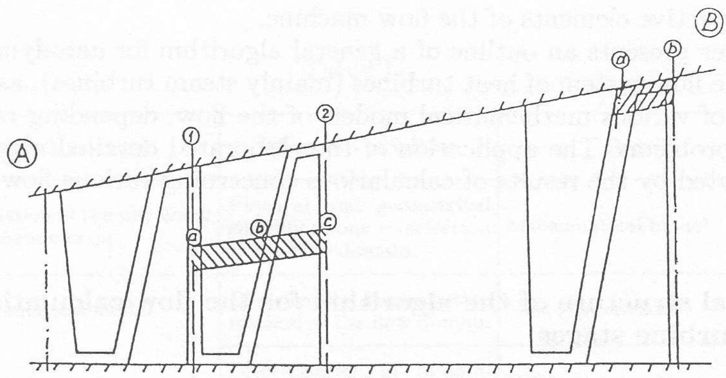

Fig. 1. An example of the composition of calculation modules.

3. Results of calculations

3.1. Analysis of applied correlations for energy losses in the turbine stage

The results of calculations carried out in compliance with the algorithm in module 0 and 1 depend, of course, on the assumed relations describing the losses of energy. From among many available relations permitting the determination of losses, the correlations suggested in [5] have been adopted. The main reason for such a choice was the extensive experimental material as well as the closed system of relations, which makes it possible to calculate all kinds of losses. The input data for the calculation of the respective components consist of the geometry of the blade system (of the blading) and the initial distribution of parameters at the inlet and outlet of the blade rows.

An important problem is the determination of the distribution of losses along the height of the blades. It is difficult to assess the various ways of distribution suggested in literature, mainly due to the scarcity of experimental information. The calculations presented in this paper have been compared with the results of measurements of the stages of a steam turbine as described in [6].
In the calculations two methods of the losses distributions along the length of the blade were used [5, 7]. The results indicate that the implemented method guarantee a qualitative agreement with the experiment. Quantitative deviations are particularly distinct in the case of the angle of outflow from the stage (Fig. 2).

Better results have been obtained assuming that the thickness of the layer in which the boundary losses are distributed is equal the one stator chord (distribution 3, Fig. 3 and Fig. 4). The advantage of the applied correlations is their analytical form facilitating their application both in analyses and in design problems. In the former case their usability lies in the determination of the share of the respective kinds of dissipating effects in the total balance of losses. In the latter case they may be easily included in the process of optimisation geometry

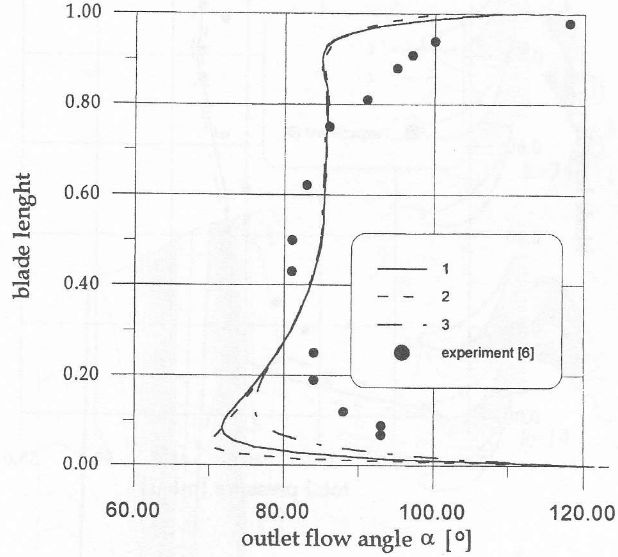

Fig. 2. Flow angle distribution at a stage outlet.

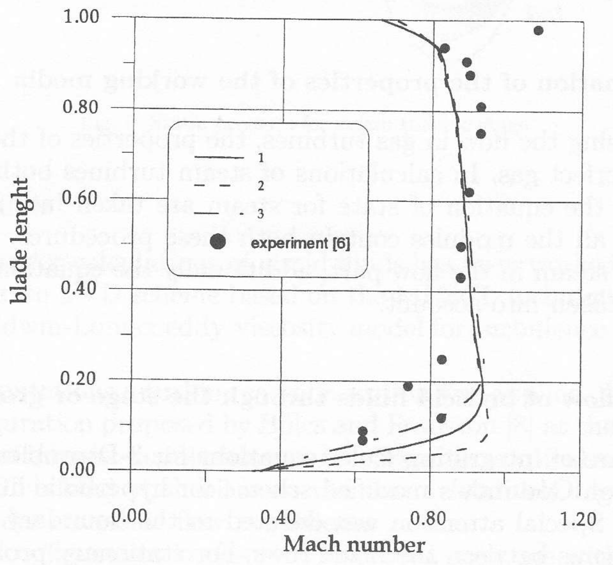

Fig. 3. Mach number distribution at a stage outlet.

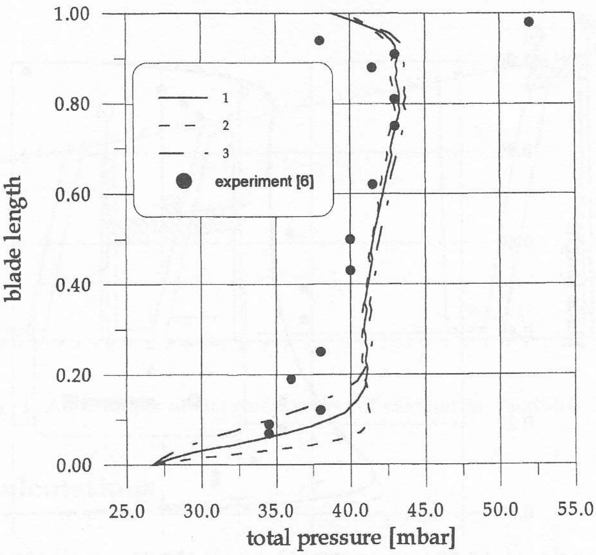

Fig. 4. Total pressure distribution at a stage outlet.

of the given stage making use of the criterion of maximum efficiency.

3.2. Approximation of the properties of the working media

While analysing the flow in gas turbines, the properties of the gas are approximated by a perfect gas. In calculations of steam turbines both the model of a perfect gas and the equation of state for steam are taken into account. Algorithms set up for all the modules contain both these procedures. Considering the condensation of steam in the flow part, additionally the equation of state for the steam must be taken into account.

3.3. The 3-D flow of inviscid fluids through the stage or group of stages

The procedure of integrating Euler equations for 3-D problems has been elaborated basing on Godunov's modified scheme for hyperbolic initial – boundary problems [2, 4]. Special attention was devoted to the boundary conditions, particularly in the gaps between the blade rows. For stationary problems (when the field of flow in the stage or group of stages is to be determined) averaging procedures have been worked out (warranting a good accuracy in the behaviour of the flux of mass in the respective cross-sections). Exemplary results of calculations of a stationary flow through the stage may be gathered from Fig. 5.

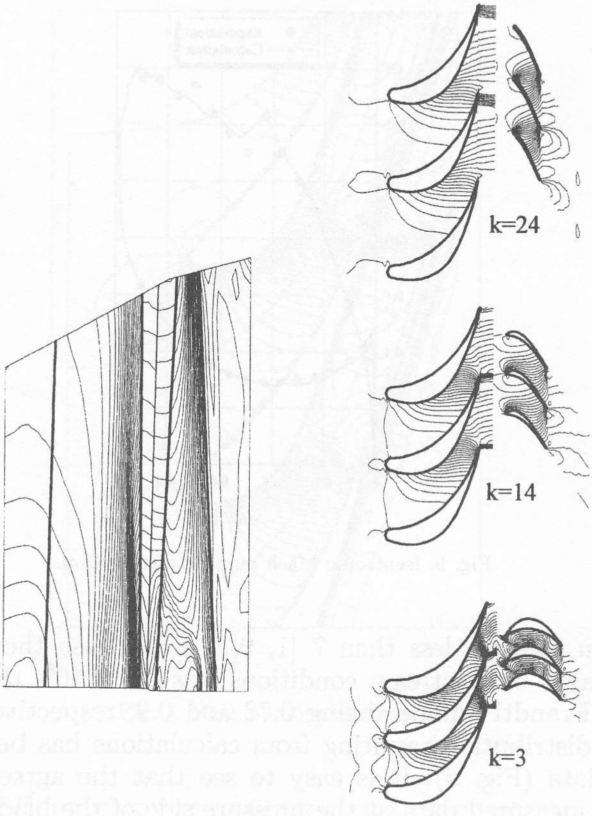

Fig. 5. Static pressure for steam turbine stage.

3.4. Viscous flow

The algorithm for calculations of viscid fluids has been worked out making use of the high accurate TVD scheme based on the MUSCL technique with Riemann Solvers. The Baldwin-Lomax eddy-viscosity model for turbulence calculations was used.

For test computations a turbine cascade section was applied. This is the fourth Standard Configuration proposed by Bölcs and Fransson [8] at the workshop. This configuration is of interest mainly because it represents a typical section of modern turbine blades. This kind of airfoil is curved, has a relatively big blade thickness and operates under transonic flow conditions.

The cascade configuration consists of 20 blades, each one with a chord 0.0744 m, the maximum thickness-to-chord ratio amounting to 0.17. The stagger angle is 56.6^o, the pitch-to-chord ratio of the cascade 0.76.

Computations have been carried out making use of a 'C'-type grid with 401 × 33 nodes. The minimum grid-line distance from the wall was chosen to achieve

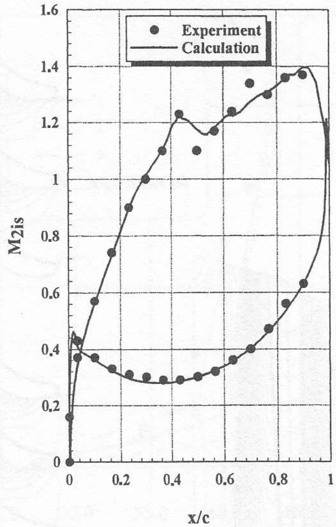

Fig. 6. Isentropic Mach number distribution.

a distance from wall y^+ less then 7 [1, 9]. In this case the Reynolds number of the chord based on upstream conditions was 0.8×10^6, the Prandtl number and turbulent Prandtl number being 0.72 and 0.9, respectively. The isentropic Mach number distribution resulting from calculations has been compared with experimental data (Fig. 6). It is easy to see that the agreement between the calculated and measured data at the pressure side of the blade is quite good. In the transonic and supersonic range at the suction side the reflection of the first shock wave, generated in the trailing edge region, has been predicted correctly, but there is no second one. This second shock wave reflection was obtained as a result of two earlier reflections, one at the suction side of the blade, the other one in the wake region. On the numerical grid applied in the calculations this second shock wave reflection at the suction side is smeared off. The calculated isolines of the Mach number have been shown in Fig. 7.

3.5. Condensation flow

Development of a new generation of steam turbines has increased the interest in the investigations of two-phase flows in the last stages of the turbine. The methods of analysing such a flow, worked out at the Institute of Power Machinery, Technical University of Silesia, are based on the solution of Riemann's initial problem concerning the real properties of steam [10]. Calculating the process of condensation, Dejc's model [11] has been adopted. Fig. 8 provides an exemplary solution concerning the channel between the blades which is characteristic for the last stages of the turbine. There is a difference between the static pressure distribution on the blade. The influence of the condensation process on the parameters

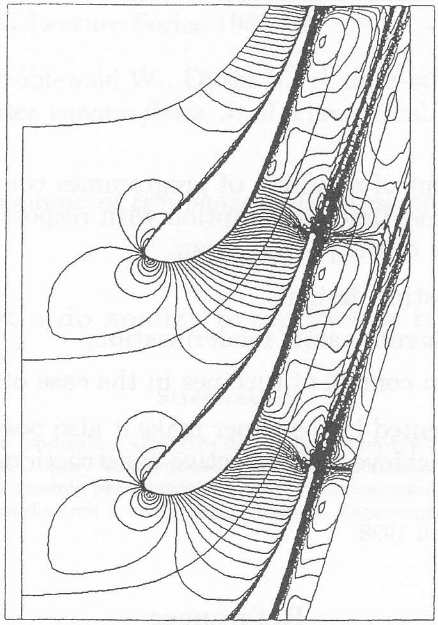

Fig. 7. Mach number contours.

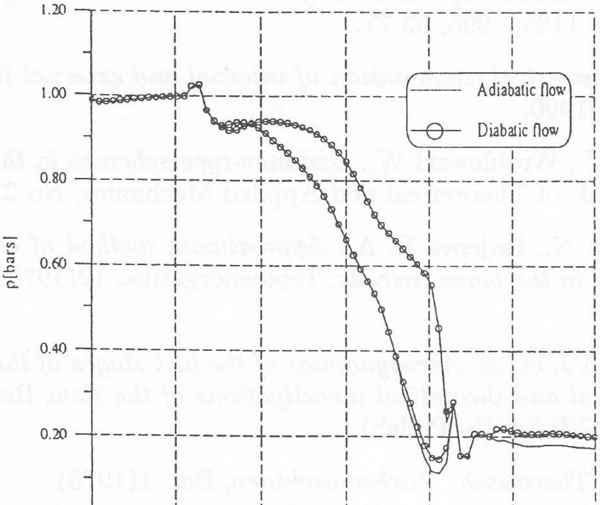

Fig. 8. Calculated pressure distribution on the blade profile.

distribution on the blade must be considered when the last stages are investigated and analysed.

4. Conclusions

The presented concept of a system of programmes complies with the criteria of economy, flexibility and time-consumption with respect to practical problems turning up in the course of the process, viz.:

- the analysis of existing designs,
- the evaluation of aerodynamic modernisation,
- the work operation control of turbines in the case of varying loads.

The algorithms presented in the paper make it also possible to solve problems of optimisation and to achieve more effective constructions of turbine stages.

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Modułowy algorytm do analizy przepływu w turbinach cieplnych

Streszczenie

W artykule przedstawiono modułowy algorytm do analizy przepływu w turbinach cieplnych. Może on mieć praktyczne zastosowanie przy konstruowaniu jak i modernizacji układu przepływowego. W algorytmie wykorzystano różne modele przepływu możliwe do zastosowania do rozwiązania konkretnych zagadnień przepływowych spotykanych w turbinach parowych. Zaprezentowano wybrane rezultaty obliczeń.