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Application of CFD methods for performance and design improvements of turbomachinery

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Abstract

The simulation of complex flow fields in turbomachines provides very important numerical data which are the base for a improvement of the all their performance. This paper includes some remarks about the application of CFD methods to predict selected flow situations in steam and gas turbines. New results has been shown for 3D flow with condensation and for the flow through channels with blade cooling by convection.

Keywords: CFD methods; Turbomachinery

Nomenclature

c	– integral energy, J	T	– temperature, °K
$E - \rho(u + \frac{1}{2}c^2)$	– velocity, m/s	u	– specific internal energy, J
M	– Mach number	ρ	– density, kg/m^2
p	– pressure, Pa	$\nu = \frac{1}{\rho}$	– specific volume, m^3/kg
R	– gas constant		

1 Introduction

The flow of gases in the flow paths of turbomachines is extremely complex. It is three-dimensional, viscous with zones of laminar, transient and turbulent motion. Various vortex structures are generated, for example in the highly loaded ducts shock waves are formed, which interact with zones strongly affected by viscous stresses. The absolute velocity is in the stage system always unsteady. In

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the case of a flow which is characteristic for non-adiabatic heat engines (cooling down of the stator blades, rotor blades, casings, rotor disks and other elements) these phenomena describe the conjugate initial-boundary value problems.

The development of numerical methods in fluid mechanics as well as the constantly growing information concerning the phenomena of dissipation of energy in fluid-flow machines have led to the development of more and more reliable methods of calculation and algorithms of aerodynamic optimization. This progress consists in the resignation of simplifications in the mathematical description of observed phenomena, the possibility of taking into account the actual geometries, a better description of the properties of the working media and the application of advanced procedures in the analysis and processing of the results of calculations.

The question arises which classes of analysis and synthesis of turbomachines can be solved at present providing information about the physics of flow processes and practical constructional premises. It is the aim of this paper to discuss this problem for some chosen cases.

2 Flow models

2.1 Equations of motion

The equation of continuity, Navier-Stokes equations and the equation of energy compose a set of equations which fully models the properties of the real flow of gas in fluid-flow machines and devices. They reflect the fundamental physical conservation laws which have been formulated for the Newtonian fluid meeting the assumptions concerning a continuous medium. In general, it may be expressed in the following way [1]:

$$\frac{\partial f}{\partial \tau} + \alpha(f) = \mu \,. \tag{1}$$

Concerning the gradient form of the equations of motion this takes a form

$$\alpha(f) = \frac{\partial}{\partial q^k} \alpha^k(f) \,. \tag{2}$$

The equations of motion may also be expressed in a quasi-linear form, and then (1) we get:

$$\frac{\partial f}{\partial t} + Pf = R, \quad P = \frac{\partial \alpha^2}{\partial f} \frac{\partial}{\partial q^k} \,. \tag{3}$$

The operators (f) and P depend on the assumed mathematical model of the described flow and the choice of the vector of dependent variables f. In the absolute coordinate system for the 'conservative' variables $f = \{\rho, \rho c, E\}^T$ in equations of motion the source term $\mu = 0$ (in the absence of a field of body forces). This property is preserved both in the case of orthogonal and not orthogonal coordinate systems. Therefore, this form is most often used to formulate initial-boundary value problems for the present stage of development of fluid-flow machines. In a relative coordinate system it is not possible to omit the source term resulting from Coriolis and centrifugal acceleration [1-4].

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, initial and boundary conditions as well as equations describing the properties of the working media. In the first stage we pass from Navier-Stokes equations to Reynolds equations averaged in time and locally in space, which require the introduction of turbulent stresses. Currently Large Eddy Simulation is discussed as promising numerical approach for unsteady turbulent flows in turbomachines also.

In Euler approximation Eq. (1) is only hyperbolic (both for $M > 1$ and $M < 1$). Disturbances (information) are, in this case, passed along the bicharacteristics, and the number of imposed boundary conditions (the number of physical boundary conditions is the number of bicharacteristics connected with the normal vector of velocity to the boundary (S_i) becoming part of the area, in which the flow is being investigated). The other conditions formulated in order to solve the given initial boundary problem are numerical conditions.

Due to the presence of diffusive parts in the equations of momentum and energy, Navier-Stokes equations get a more complex mathematical structure than the Euler equation. The equations of momentum and energy are parabolic equations versus time and space, and elliptical equations versus the spatial coordinates of stationary flows. The equation of continuity is hyperbolical for both cases. In the case of actually occurring situations the initial boundary problems (or boundary problems) formulated in relation to a full set of equations of conservation are hybrids in their character: parabolic-hyperbolic in the case of non-stationary flows and elliptically-hyperbolic in the case of stationary phenomena. This fact renders it difficult to discuss the boundary conditions while taking into account the general conditions of the flow fluids. In the case of non-steady flows is very important to impose the non-reflecting boundary condition [5].

2.2 Modelling of Reynolds stresses

In order to average the Navier-Stokes equation in compliance with the Reynolds or Favre conception we must determine the tensor of Reynolds stresses as a function of independent variables. These dependencies vary in their structure and have often been called models of turbulence. They may be divided into two groups [1]. To the first group belong models introducing the notion of turbulent viscosity, the crucial notion of the Boussinesq hypothesis. The fundamental basis in the classification of models in this group (nowadays called methods of the first order) is the number of differential equations of transport of definite quantities which are characteristic for the turbulent flow. Thus we may speak of zero-equation (algebraic), one-equation, two-equation models etc. Models of the second order are formulated making use of transport equation for the Reynolds stresses. From the various ways and methodological assumptions, applied to determine the respective terms to this equation, there result various concrete propositions of closing hypotheses [1, 2, 6-8].

Due to the complex character of the flow of fluids through the ducts of turbomachines none of the models of turbulence set up so far may be considered to be universal.

From among the group of algebraic models of turbulence the most often applied is the Baldwin-Lomax model (B-L) [9]. The simplified physical premises, basing on which zero-equation models have been developed, (among them the model
B-L) make it possible to obtain satisfying solution only in the case of simple flow structures. Basing on numerous investigations and calculations [9, 10] we may say that:

- the considered models are adequate in the case of two-dimensional flows of compressible fluids with moderate pressure gradients,
- they may be applied for three-dimensional boundary layers with slight secondary flows,
- they are not of much use in the case of flows with strong curvatures of the stream line, Coriolis acceleration, centrifugal acceleration and separations of the boundary layer,
- they are of no use for the intake of secondary flows generated by pressure gradients, turbulence and flows with considerable variations of tangential stresses,
- they do not describe satisfactorily the effects of shock waves with the boundary layer.

In the case of two-dimensional flows with moderate pressure gradients no effects were to be observed when they were replaced by 'physically' more advanced models. Quite good results have been obtained in investigations of a flow with positive pressure gradients flows affected by shock waves in a zone with a boundary layer (in the two-dimensional geometry) applying the Johnson-King's model [11].

For flow structures, which are characteristic for turbomachines, several two-equation models have been developed, paying much attention to an improvement of the $k - \varepsilon$ model. In spite of a considerable progress, if compared with zero-equation models, this model does not warrant good results either, concerning all the possible flow structures in the ducts of fluid-flow-machines. For two-dimensional flows the mean velocity profiles and main characteristics of turbulence can be calculated rather accurately. In the case of the 3-D geometry is generally not possible to attain a high accuracy as far as intensive secondary flows and shock waves are concerned. This model renders bad results in investigations on the flow through the rotating ducts with curvatures and separation.

From among various ways of enlarging the range of application of this kind of models attention ought to be drawn to its combination with algebraic Reynolds stress models as suggested by Rodi [2] and further developed in [12] and [13]. This model takes into consideration the influence of curvatures and accelerations at a relative flow. Other possibility is to use the non-linear turbulence models [12].

As the equations of transport of Reynolds stresses are rather complex, they are rarely used in investigations of turbomachines. The available results indicate, however, that they are highly promising [2].

2.3 Equation of state

The flows calculations in turbomachinery are made usually using the ideal gas equation of state. For the gas such as water steam in superheated and supersaturated state this assumption decreases the solution accuracy. On the other hand, adaptation of the real gas equations of state to the numerical calculation of the flow in turbomachinery channels causes significant increase of the computational time. The compromised approach is the application of the 'local' real gas equation of state [14, 15]. The mathematical form of this equation is similar to the virial equation of state with one virial coefficient:

$$\frac{p\nu}{RT} = A(T) + B(T)\frac{1}{\nu}\,. \tag{4}$$

Where $A(T)$ and $B(T)$ are the polynomials, whose coefficients are only functions of the temperature and are determined on the basis of approximations of the fundamental equations of state (IAPWS'97 [16]).

3 General analysis of the solved problems

3.1 Numerical schemes and algorithms

From among the three main groups of methods finite difference, finite-elements and finite-volumes methods the latter one forms the fundamental basis of many codes of calculations (Euler and Navier-Stokes equations) applied in turbomachines. In the case of compressive flows (particularly in areas of transonic flows) for the approximation of convective terms 'upwind' methods are widely used, mainly those of the Godunov type, which apply Riemann problems for the purpose of determining the parameters between the nodes of the numerical grid. These methods are also known as methods of 'Flux Difference Splitting' – FDS. In contradistinction to finite differences, schemes of the 'upwind' type take into account the characteristic directions of the propagation of disturbances in the flow. If additionally such procedures are applied as limiting functions, schemes with Total Variation Diminishing properties, they allow a highly accurate determination of such distinct phenomena as shock waves and tangential discontinuities without unnecessary numerical oscillations.

Diffusive terms are usually approximated in a similar way as parabolic equations.

A discretisation relative to time is obtained by the application of the Lax-Wendroff formulation, Beam and Warming schemes or Runge and Kutta method.

3.2 Stationary flow

Investigating the stationary flow in the individual ducts of turbomachines (heat turbines and compressors) with intensive discontinuities much information can be obtained when integration algorithms of Euler equations are used. Both the localisation and intensity of the discontinuities have been correctly simulated for complex geometries. Also the application of this type of codes in the optimisation of ducts has made it possible to create new constructions of blade systems. In the case of stationary flows generally also commercial codes are applied based on Navier and Stokes equations and selected models of turbulence. Thanks to their application it is easier to understand the processes of the generations of secondary flows and the energy analysis of cascade flows [17, 18].

Codes which are based on Euler equation and combined with correlation describing the losses of mechanical energy constitute the basis for discussions concerning the flow characteristics for stage groups and whole flow systems.

In the range of three-dimensional stationary flows further investigations should aim at the authentification of simulations of the dissipation effects of and thermal load (including non-adiabatic flows).

3.3 Non-stationary flow

The ability to determine quantitatively non-stationary effects in turbomachines, brought about by the mutual interactivity of the respective blade-row, is of fundamental importance for the improvement of the energy conversion efficiency. Periodical disturbances caused by these interactions comprise both large scale duct structures of secondary flows and small-scale vortices of aerodynamic traces as well as thermal disturbances. The analysis of such flow phenomena generally requires sophisticated codes for numerical integration of Navier-Stokes non-stationary equations. The transport of secondary fluids through the impeller (rotor) duct can in general be easily recognized basing on Euler non-stationary equations, particularly if we do not take into consideration the evolution of the boundary layers. In other cases (among others: in the case of prediction of the processes of separation or the effect of shock waves on the boundary layer etc.) complete flow models must be applied. The algorithms at our disposal do not quite allow a reliable discussion about these problems. What is needed, is some progress in the physical modelling of the interaction between disturbances and discontinuities on one hand, and the flow zones with an essential influence of viscosity on the other one.

3.4 Multiphase and multicomponent flows

The solution of problems concerning cavitation, dust and water erosion, the condensation flow in steam turbines and the flow accompanied by combustion requires a continuous improvement of the methods of investigating multicomponent and multiphase flows. In the case of some new energy techniques these problems acquire additional importance. This concerns particularly flows in gas turbines, in installations in which coal is burned directly, in combined cycles integrated with coal gasification, as well as in pressure-combustion systems. Transonic flows with condensation are characteristic for the last stages of modern steam turbines. The equation of the growth of water drops takes into account changes of the values of over-cooling in time as well as the actual properties of steam. The method developed has been applied to several test cases. Calculation results were presented in some papers [5, 14, 15, 19]. In the Fig. 1 has been shown the static pressure distributions for adiabatic (a) (without condensation) and diabatic flows (b). The calculations were made for chosen meridional plane of the 200 MW turbines stage. The distribution of the wetness fraction (a) and nucleation rate (b) [20].

3.5 The cooling of the blade system

Aircraft engines and stationary turbines are nowadays cooled down by means of air supplied by compressors. Techniques of closed steam cooling (in gas-steam systems) are presently being investigated; simultaneously the application of thermosiphons and heating pipes in cooling systems are investigated.

The fundamental problem for internal flow in cooling passages is modelling of

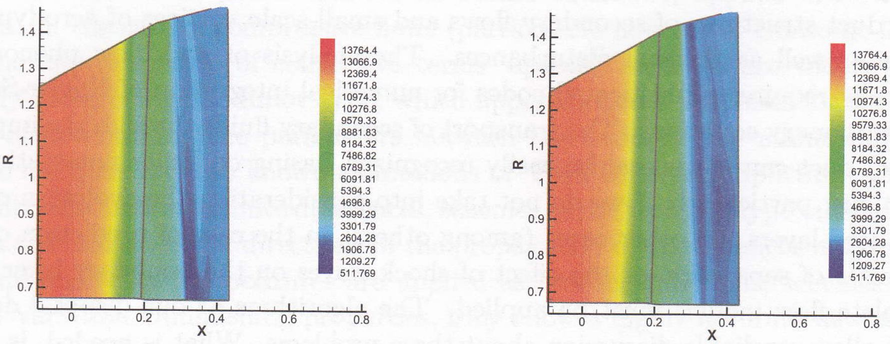

Figure 1. Static pressure distribution, a) adiabatic flow; b) diabatic flow.

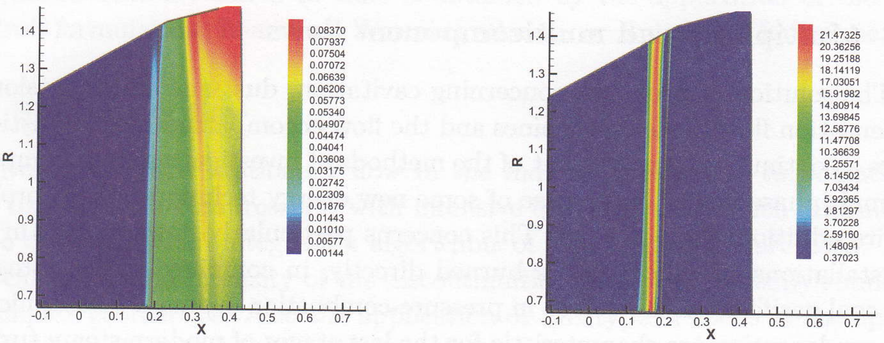

Figure 2. a) Distribution of the wetness fraction; b) nucleation rate distribution.

turbulence, as the flow structure and the influence of curvatures and the Coriolis force on the stability of the hydraulic and thermal temperature boundary layer is rather complex. An important trend is the investigation of the sensitivity of the respective models to changes of the fundamental parameters of the flow. [21]. The problem of the right choice of a model is far from being solved. The present state of researches suggests the necessity of further investigations on combined $k - \varepsilon$ models and the algebraic model of Reynolds stresses (ARSM) and also of wider investigations concerning the application Reynolds stress model in the case of such complicated flow structures.

Analysing the external cooling (flow around the blades) considerable difficulties are encountered in the case of non-stationary transonic flows and the application of film and diffusion cooling. Classical models of turbulence, including

ARSM, do not comprise all the phenomena characterising this flow, therefore a further progress will be possible only when models of the second order have been developed and applied.

In general formulation the problem of the blade cooling is coupled. The model of the flow and hat transfer includes: RANS equation, turbulence modelling for external and internal flows, Fourier equation governing temperature distribution in a blade structure and the appropriate initial and boundary conditions.

Figures 3 and 4 show some calculation results for the blade cooled by convection. The heat transfer problem is solved using the finite element method and the flow problem is solved using the finite volume method. Calculation domains are discretised by structured C-type grid for the flow domain, and unstructured grid for heat conduction.

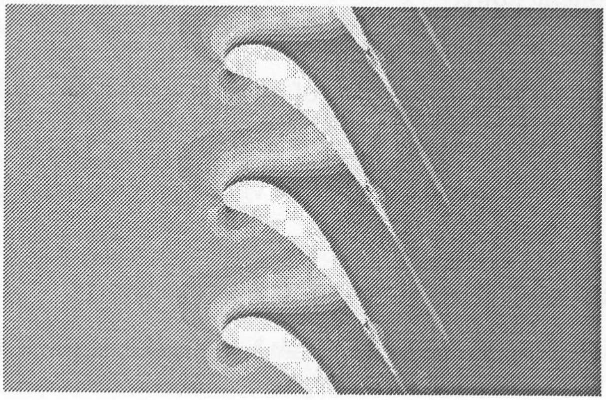

Figure 3. Mach number distribution.

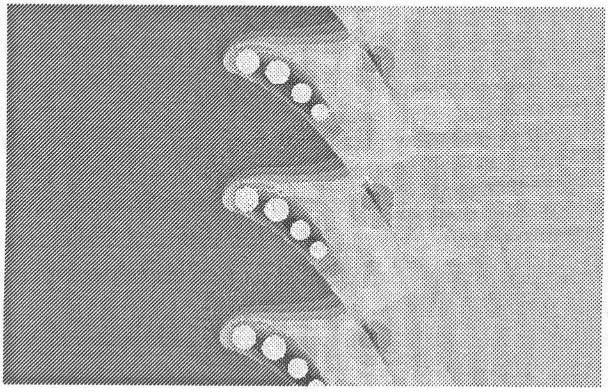

Figure 4. Temperature distribution in the blade and flow.

4 Conclusions

Available algorithms for the solution of Euler and Navier-Stokes equations enable us to obtain a lot of quantitative and qualitative information about phenomena connected with the conversion of energy in turbomachines.

Researches in the field of fluid mechanics and heat exchange as well as of combustion are concentrated at present on the following problem:

- attempts to find adequate models of turbulence comprising all the fundamental processes and phenomena (laminar-turbulent transitions, the effect of shock waves, separation, the influence of curvatures, Coriolis acceleration, buoyancy effect, the lack of isotropy etc.),
- the development of fluid mechanics and thermodynamics of multiphase and multicomponent flows,
- unsteady flow in blade systems,
- the development of new schemes of integrating Navier-Stokes's equations,
- the generation of self-adapting and non-structural calculation grids,
- the elaboration of algorithms for the visualisation of flows.

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