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Numerical evaluation of the blade cooling for the supercritical steam turbine

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HIGHLIGHTS

► Numerical solution of the CHT problem for the blade channel of supercritical steam turbine.
► The determination of the potential possibilities of using the martensitic steel for the first blades.
► Different cooling steam parameters, different turbulence levels of the main flow and the thermal barrier are examined.
► The obtained results determine the thermal potential of the applied method of the blade cooling.

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ABSTRACT

Steam turbine systems for supercritical parameters are one of the most important directions of the development of conventional power plants. A steam turbine working in such cycles has to be adjusted to operation with higher and higher steam temperatures. The aim of this analysis is to determine the cooling conditions of the blades of the steam turbine first stage. The cooling is supposed to ensure that the same materials as those used for the live steam temperature of 873 K are used for the first blades operating with the live steam temperature of 923 K. In the calculations the Conjugate Heat Transfer (CHT) model is used to simulate the following phenomena: the fluid flow in the blade-to-blade cascade, the heat transfer in the blade and the coolant flow in the holes. Analyses of different cooling steam parameters and of different turbulence levels of the main flow are performed. The problem is analysed for the steam conditions corresponding to the first blade of High Pressure (HP) and Intermediate Pressure (IP) turbines, respectively. For the HP turbine the on-blade thermal barrier is considered as an additional mean to reduce the metal temperature to the limit required.

1. Introduction

The development of modern power engineering technologies using gas and coal fuels is motivated mainly by the increase in the power generation efficiency and a reduction in the environmental impact of such systems. One of the directions to achieve these objectives is the rise in the working medium temperature at the thermal turbine inlet. This concerns both the gas and steam turbine.

Steam turbine systems for supercritical parameters are one of the most important directions of the development of conventional power plants. Due to such technologies, it is possible to obtain the efficiency of electricity generation exceeding 50% [1]. Therefore, the steam turbine working in cycles with the steam supercritical pressure will have to face higher and higher thermal loads. It is anticipated that the steam temperature in the planned supercritical power units will be by 50–100 K higher than in supercritical plants already in service. Achieving the respective temperature and pressure values exceeding 900 K and 30 MPa at the inlet calls for particular attention paid to the turbine nodes operating in these conditions. Designing them, the choice has to be made between using a new material which is more resistant to thermal loads but expensive, or introducing thermal screens and organising local cooling in the flow system. The former will require a wider application of materials made of nickel alloys. The latter might allow the use of materials which are currently used in facilities with lower steam parameters. The influence of thermal screens and external cooling on the rotor thermal load in the live steam inlet area was investigated by Kosman [2]. Design solutions specific to supercritical steam turbines make it possible to keep the thermal load and stresses in the turbine components at a reasonable level [2].

The application of convective cooling to the blades of the first stage of the HP and IP parts of the steam turbine for supercritical steam

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List of symbols

c_p	specific heat capacity at constant pressure, J/(kg K)
c	chord, m
c_x	axial distance of chord, m
H	specific enthalpy, J/kg
h	heat transfer coefficient, W/(m^2 K)
k	turbulence kinetic energy, J/kg
M	Mach number
p	static pressure, Pa
Re	Reynolds number
s	curvilinear coordinate from the leading edge along the profile curve, m
t/c	pitch to chord ratio
T	static temperature, K
y^+	dimensionless distance
x	axial coordinate, m

Greek symbols

λ	thermal conductivity, W/(mK)
ρ	density, kg/m^3

Indices

0	total parameters
1	inlet
2	outlet
c	coolant
s	isentropic

parameters is an additional option which may be considered for new designs. Only convection cooling should be taken into account for this case due to the parameters of steam which are available in the steam cycle and which may be used as the cooling agent.

In the search for solutions to problems related to the cooling of steam turbine blades, the experience gained from research conducted on the cooling of gas turbines should be employed. Tracing back the evolution of cooling techniques in these turbines, it turns out that at first convection cooling solutions were used. More effective cooling systems were introduced later, such as film cooling or transpiration cooling. Dunn [3] analyses a wide spectrum of problems related to the blade profile aerodynamics and the heat transfer in various cooling methods applied in gas turbines.

To protect the gas turbine blade thermally, an on-blade thermal barrier is used. The assessment of this solution for a selected gas turbine was carried out in [4] using advanced numerical models. This type of solution may also be considered as an option for steam turbine blades.

In problems related to convection cooling of blades, the determination of the flow field parameters is the basis for the calculation of the heat transfer in the turbine components. Due to the very complex flow structure and the high sensitivity of the heat transfer conditions to changes in this structure, the accuracy of the heat transfer coefficient calculations in the range of $\pm$10% is considered as good. In more complex areas, the differences between calculation results and measured values may reach 30% and more.

The progress in the development of computational methods in the last dozens of years has allowed a transition from correlation relationships on a flat plate, through the use of algorithms with coupled solutions for the boundary layer and the main flow for complex geometries, to methods based on solving Navier–Stokes equations. Despite that, taking account of all the flow modelling phenomena is still a computational challenge. It is a difficult task because in such problems the weak points of the turbulence and the laminar–turbulent transition models become more visible.

Many heat transfer problems in the turbine are analysed assuming steady conditions. And this happens despite the fact that the blade operating conditions are highly unsteady and the blade is subject to the impact of the blade wake. Taking these phenomena into account calls for a much longer computational time.

There is some hope for a more precise description of the flow phenomena in the use of the Direct Numerical Simulation (DNS) methods, with no application of procedures of averaging flow values. However, these are not the methods that could be used for complex geometrical systems in the very near future for the fluid flow problems, especially in the coupled problems with the heat transfer in solids.

A detailed determination of flow structures is much more significant in the case of film cooling. For these problems, the conjugate algorithm methods are extended with the Large Eddy Simulation (LES) method, which however is much more demanding towards the numerical mesh than the methods based on the Reynolds-averaged Navier–Stokes (RANS) equations and which requires much longer computation times [5,6]. Coupling the LES method with the heat transfer algorithm for a gas turbine blade with film cooling is presented in [6]. However, the results of the performed simulations differ considerably in terms of quantity from the experimental data obtained from the RANS computations.

Turbulence models thus remain, for the time being, the only effective way for most analyses of technical issues. The modelling methods which are most often used to model turbulence in fluid flow and heat transfer problems in the blade-to-blade cascade are the two-equation models of eddy-viscosity. These models are a compromise between complexity and accuracy. Their usefulness in terms of the heat transfer coefficient determination was studied among others in [7] and [8]. In [8] comparative studies of the v2f model were conducted in conjugate computations for a blade with convective cooling. In [9] a comparative analysis is presented to study the ability of three turbulence models to predict film cooling and to assess the influence of the grid type on the solution. The results confirm that conjugate heat transfer models predict a significant difference in the temperature predictions in comparison with adiabatic models. The realizable k–ε, and the shear stress transport k–ω (SST) turbulence models present a satisfactory agreement with experimental data. The interaction between the flow field and temperature field in the cooled blade makes it necessary to combine the flow problem with issues related to the heat transfer in a solid. The Conjugate Heat Transfer (CHT) calculations have their specificity and impose higher requirements, especially on the flow part calculations. This concerns, among others, the numerical mesh parameters near the wall to appropriately determine the temperature profile of the boundary layer. The publications presenting the solution to the Conjugate Heat Transfer problem for the turbine blade usually ignore the laminar–turbulent transition (e.g. [10–12]). The variability of the transition models proves how difficult it is to model this phenomenon. A comparative study of bypass transition models was presented in [13]. The models were validated against experimental data from different test cases including the turbine channel flow. The model which has gained much popularity in engineering applications is the Gamma–theta model (e.g. [14,15]). The reason for this is its universality and availability in the ANSYS CFX software package.

Using transition models in the CHT calculations makes it possible to obtain better results, both quantitatively and qualitatively.

The gas turbine blade convection cooling technology may be used for supercritical steam turbines. The modelling of the flow