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Study of the wet steam flow in the blade tip rotor linear blade cascade

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ABSTRACT

Experimental investigations of non-equilibrium spontaneous condensation in transonic steam flows in a linear blade cascade were carried out. The cascade consists of the rotor blades of the low-pressure (LP) steam turbine last stage. The experimental testing facility is a part of a small-scale steam power plant located at the Silesian University of Technology in Gliwice. The steam parameters at the testing facility inlet correspond to the wet steam conditions in a low-pressure steam turbine. Static pressure measurements on the blade surface as well as Schlieren images were used to assess the flow field in the steam turbine rotor tip blade linear cascade for different flow conditions. The experimental results were used to validate an in-house CFD code.

1. Introduction

Steam turbines are the main part of fossil and nuclear electric power generation plants. In contrast to the condensing steam turbine of nuclear power plants, most steam turbines in fossil-fired power plants operate in the sliding pressure mode and under different loads, from full to part-load conditions. This is mainly associated with the coexistence of fossil-fired power plants in the system with technologies utilizing renewable energy sources, which are in a privileged position. Off-design or part-load operation of the condensing steam turbine usually involves a drop in the turbine efficiency, which especially affects the last stages of the low-pressure part. The working conditions of the condensing steam turbine last stages are also very sensitive to the condenser parameters and the vacuum quality, which is mainly related to the condenser cooling system. Fossil-fired steam power plants usually use closed cooling systems with wet cooling towers where the condenser pressure depends on atmospheric conditions.

Consequently, it is obvious that the condensing steam turbine last stages may operate under various working conditions due to changes in pressure and temperature upstream the stage and in static pressure at the stage outlet.

In large-capacity steam turbines, the state path for the nominal load usually crosses the saturation line in penultimate stages. This means that at least the last two stages of the low-pressure (LP) steam turbine operate in the two-phase region (wet steam), producing much more than 10% of the total power output. The condensation process in steam turbines takes place in the last stages of the low-pressure part at a very high velocity of steam, in transonic flow conditions. Steam condensation occurs when the steam temperature drops below the saturation point at a given pressure. The losses in the LP steam turbine last stages are difficult to estimate, both experimentally and numerically. Steam has to be treated as a real gas, the flow has a two-phase character, it is transonic and strongly three-dimensional. Two types of losses have to be taken into account in this case: gasdynamic losses, caused by the interaction between the fluid and the wall boundaries, and thermodynamic ones, generated during the phase change. Beside the drop in efficiency the condensation process leads to blade erosion of the LP condensing steam turbine last stages, which creates serious maintenance problems.

The problem of loss prediction in turbomachinery has been the focus of interest of many researchers. Numerical research in this field is a complex task. Steam has to be considered as a real gas and both homogeneous and heterogeneous condensation need to be taken into account. The wet steam flow investigations are of practical importance in a number of engineering applications, not only in transonic/supersonic nozzles or low-pressure steam turbines. The condensing steam flow has been studied for many years, both experimentally [1–11] and numerically [8,11–13]. However, the numerical models and the CFD methods modelling the flow still lack sufficient experimental data for validation. This paper presents and discusses the results of experimental and numerical studies of the wet steam flow through the rotor blade tip area of a linear cascade.

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Nomenclature

c	absolute velocity, $m \cdot s^{-1}$ (or blade chord, m)
M	Mach number
p	pressure, Pa
r	radius, m
t	temperature, °C
u	circumferential velocity, m/s
v	velocity, m/s
w	relative velocity, m/s
x	axial direction, m

Greek letters

β	relative velocity angle, °
ζ	loss coefficient, –
Δt	superheating, °C
Θ	circumferential direction, °
ω	angular velocity, s^{-1}

Subscripts

0	total parameters
in	inlet conditions
out	outlet conditions
l	liquid phase
s	isentropic
v	vapour phase

It is obvious that an axial turbine stage consists of a row of stationary stator blades (vanes) and a row of rotating rotor blades. A typical last stage of the low-pressure steam turbine blading in the Θ-x plane at the tip section is shown in Fig. 1, together with the velocity triangle between stationary and moving blades.

There are a lot of reasons why the flow in the rotor tip part of the steam turbine last stage is so important from the point of view of maintenance and gasdynamics. The main of them are:

- The velocity triangle illustrating the flow in the turbine blading (Fig. 1) shows that a high-degree reaction takes place in the tip part of the steam turbine last stage. This means that the drop in static enthalpy in the row of the rotor blades is much higher than in the stator.
- At design conditions, a typical spanwise variation of the reaction in the LP steam turbine last stage is from about 0.15 at the hub to over 0.65 at the tip. This may affect, due to a reduction in the mass flow rate for partial loads, the separation zone close to the root downstream the last stage and also the torus vertex close to the casing in the axial gap between the stator and the rotor blade, ahead of the tip part of the rotor blades.
- The flow into the rotor blades may be subsonic or supersonic. For very long blades in the tip area, the relative inlet velocity to the rotor may be higher than the local speed of sound, due to the high value of circumferential velocity u ($u = \omega \cdot r$). The supersonic inflow is the main cause of an additional rise in losses due to the shock wave generated upstream the rotor blades. It may also prevent the mass flow rate through the blades from reaching the design value.
- Due to the transonic character of the flow field in the rotor tip area (in a relative coordinate system), a very complex shock wave structure appears. This phenomenon has a very strong impact on gasdynamic and thermodynamic losses.

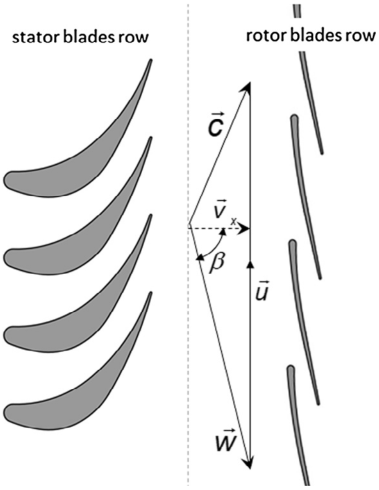

Fig. 1. Steam turbine typical last stage at the tip section and the velocity triangle.

The reasons mentioned above encourage further studies into the flow through the tip area of the rotor blades of the LP steam turbine stages. It is very difficult to investigate the flow in the last stage in a real steam turbine experimentally. It is much easier to perform experimental measurements on the linear blade cascade, mainly in order to provide validation data for the numerical models used in CFD codes. The flow through the rotor blade cascade in the tip area was already investigated by Bakhtar et al. [1,2].

Experimental and numerical analyses of the stator blades linear cascade were performed by the authors for different flow conditions [13]. This paper presents the results obtained for the tip area of the rotor linear blade cascade for the same steam turbine last stage. The analysis was conducted using the analogous experimental and numerical tools.

Nowadays, the research issues connected with the steam condensing flows investigation are still valid and are under consideration of many researchers, as for the nozzles [14] or turbine stages [15–17].

2. Research methodology

2.1. Experimental facility

The rotor blades linear cascade was used in experimental testing carried out for condensing steam flow conditions. The geometry of the blades under analysis corresponds to the real rotor blade geometry of an outdated 200 MW_e steam turbine last stage. The blades were enlarged 2.5 times to properly adjust their size to the testing facility and to create a better opportunity to perform the static pressure measurement on the blade surface. Unfortunately, after the cascade was scaled up, it was still too small to use the in-house wet steam probe for accurate measurements of the wetness mass fraction and the mean droplet radius. Therefore, the flow field Schlieren photography and the static pressure measurement on the blade surface were used in the experiment only.

The flow through the blade tip area of the rotor blade cascade was investigated experimentally in a relative coordinate system (Fig. 2), where the inflow was directed horizontally and the rotor blade cascade was arranged in the testing facility by rotating it