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Research paper

Effects of surface roughness on deviation angle and performance losses in wet steam turbines

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HIGHLIGHTS

- Two-phase turbulent transonic steam flow is numerically studied in this paper.
- As a result of condensation, aerothermodynamics of the flow field changes.
- Surface roughness has almost negligible effect on deviation angle.
- Surface roughness plays an important role in performance losses.
- Contribution of different loss mechanisms for smooth and rough blades are computed.

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ABSTRACT

In this paper, effects of turbine blade roughness and steam condensation on deviation angle and performance losses of the wet stages are investigated. The steam is assumed to obey non-equilibrium thermodynamic model, in which abrupt formation of liquid droplets produces condensation shocks. An AUSM-van Leer hybrid scheme is used to solve two-phase turbulent transonic steam flow around turbine rotor tip sections. The dominant solver of the computational domain is taken to be the AUSM scheme (1993) that in regions with large gradients smoothly switches to van Leer scheme (1979). This guarantees a robust hybrid scheme throughout the domain. It is observed that as a result of condensation, the aerothermodymics of the flow field changes. For example for a supersonic wet case with exit isentropic Mach number $M_{e,is} = 1.45$, the deviation angle and total pressure loss coefficient change by 65% and 200%, respectively, when compared with dry case. It is also observed that losses due to surface roughness in subsonic regions are much larger than those in supersonic regions. Hence, as a practical guideline for maintenance sequences, cleaning of subsonic parts of steam turbines should be considered first.

1. Introduction

Blade surfaces in steam turbines experience significant performance degradation during operation. Thermal erosion, fouling, and collision of particles and impurities over blade surfaces increase the surface roughness that adversely affects the stage performances. As a source of roughness, silica (Sio_2), for example, in steam/water circuit plays a special role because of its high solubility in steam. As steam cools down in low pressure ends of the turbine, the dissolved silica in steam deposits over the blades. As a result, silica generates a coating over the blades surfaces that even with acid, is really hard to be removed.

The effects related to the blade surface roughness are well-known issues for turbomachinery designers in particular, when dealing with the estimation of the components' performance losses. Several studies have been performed in this subject both experimentally and numerically. Bammert and Sandstede [1] studied surface roughness effects in a turbine blade cascade and showed that due to the blade roughness, start of turbulent boundary layer approaches to the leading edge. Then, Arts et al. [2] experimentally investigated the linear VKI cascade of a gas turbine. They studied the effects of different flow conditions (Mach number, Reynolds number and free-stream turbulence intensity) on the aerodynamic performance and heat transfer. In 1998, Kind et al. [3] investigated the roughness effects at different locations of stator and rotor in a turbine cascade and found that roughness effect on the suction surface is more important than the pressure surface.

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Then, Yun et al. [4] presented measurement and a mean-line analysis of turbine efficiency reduction due to blade surface roughness. Performance tests were conducted in a low-speed, single-stage, axial flow turbine with roughened blades. Afterwards, Zhang et al. [5] studied the influence of surface roughness on the aerodynamic losses of a turbine vane. They employed the non-uniform, irregular and three-dimensional roughness on the tested vanes.

In 2013, Im et al. [6] investigated the effect of leading edge roughness and Reynolds number on the compressor profile loss. They found a high impact of blade roughness on the performance. This was mainly due to the influence of the rough surface on the suction side laminar separation bubble. Vazquez and Torre [7] and Hodson and Howell [8] studied the effect of surface roughness on the efficiency of low pressure turbines at high altitude operating conditions. Recently, Bellucci et al. [9] studied the influence of roughness on performance of a high pressure steam turbine stage operating in the dry conditions. Unsteady effects that may affect the influence of the roughness, such as the upcoming wakes on the rotor blade, were taken into account. The analysis of the data highlighted the effect of roughness on boundary layer transition, and the associated profile losses increase.

Several numerical researches have been performed about the surface roughness effects too. Many efforts were made to take into account the roughness with an appropriate wall boundary condition for the turbulence model. In 1978, Cebeci and Chang [10] introduced a model to account for the surface roughness effects and applied it to boundary layer equations. Boyle and Civinskas [11] studied the heat transfer rate of a rough flat plate and a rough turbine blade using Navier–Stokes quasi-three-dimensional thin layer analysis and Cebeci-Chang roughness model. Then, Boyle [12] studied changes in the efficiency of a two-stage turbine using Navier–Stokes analysis for a range of incident flow angles and blade surface roughness heights. It was shown in this study that Navier–Stokes analysis is a useful tool for prediction of the change in the turbine efficiency at off-design conditions caused by surface roughness.

In 1998, Guo et al. [13] used a three dimensional CFD code to predict local Mach number and heat transfer coefficients over airfoil surfaces and end-walls of a transonic gas-turbine nozzle guide vane. They modified the law of the wall for calculation on rough surfaces and their results were confirmed by the measured data. A comparison between the results obtained with the Cebeci and Chang [10] and the Wilcox roughness models were presented by Boyle and Senyitko [14]. Good results were obtained using the Cebeci model coupled with Mayle's [15] transition model. Then, Shabbir and Turner [16] modified Spalding's formula to predict skin friction of rough surfaces and validated their code by comparing the results with measured rough cascade data by Bammert and Milsch [17].

Different turbulent models have been used to investigate the roughness effects. Yershov et al. [18] indicated that the SST turbulence model has an upper hand over the BL turbulence model in simulation of transonic compressor flows. Then, a numerical and experimental investigation of the effects of roughness in compressor blades was carried out by Mesbah et al. [19]. They compared the results obtained using three different turbulence models (k-L, k-ω and Spalart–Allmaras) with the measurements in terms of blade load distributions and losses.

According to the literature review, it can be seen that most of the researchers have studied surface roughness effects in the compressors, gas turbines and high pressure steam turbines. In fact no study has been performed about the roughness effects on the performance of low pressure steam turbines operating under two-phase flow conditions. These conditions exist at the last stages of the steam turbines that lead to additional losses.

In the past, several upwind schemes have been developed and successfully used for the calculation of many problems. Prominent representatives of this class of algorithms are schemes based on the flux vector splitting and flux difference splitting concepts. Classical flux vector splitting methods are simple and very robust upwind techniques but they exaggerate diffusive effects which take place in shear and boundary layers. On the other hand, schemes based on flux difference splitting are very accurate for viscous calculations, but at the cost of increased computational expense. Moreover, they lack robustness for flows with strong expansions into regions of low pressure and low density.

The Advection Upstream Splitting Method (AUSM) retains the robustness and efficiency of the flux vector splitting schemes but it achieves the high accuracy attributed to schemes based on the flux difference splitting concept. This method was suggested in 1993 by Liou and Steffen [20].

They used it to solve some problems (e.g. inviscid calculation of NACA 0012 airfoil, 2D supersonic flow over a circular blunt body) and compared the results with other methods (Roe, Van Leer). Based on their results, the special merits of AUSM compared to other upwind schemes are the low computational complexity and the low numerical diffusion.

The application to various relevant flow problems, however, has shown that the AUSM method has several deficiencies. It locally produces pressure oscillations in the vicinity of shocks. Furthermore, the scheme has a poor damping behavior for low Mach numbers which leads to spurious oscillations in the solution and affects the ability of scheme to capture flows aligned with the coordinate grids. In order to improve the shock resolution capability and the damping behavior of AUSM, in particular, a hybrid method was introduced by Radespiel and Kroll which switches from AUSM to the van Leer scheme at shock waves [21]. This ensures the well-known sharp and clean shock capturing capability of the van Leer scheme and the high resolution of slip lines and contact discontinuities through AUSM. The hybrid method was used to solve some inviscid and viscous single-phase problems (e.g. calculation of RAE 2822 airfoil, flow over a compression ramp) by Radespiel and Kroll [21].

Paillere et al. extended the AUSM$^+$ scheme to compressible two-fluid models for gas/liquid flow and used it to solve some two-fluid air/water flow benchmark problems from nearly incompressible flows to fully compressible flows [22]. Niu and Lin proposed a modification of pressure–velocity diffusion terms in AUSM to compute the compressible cavitated flows based on single and two-fluid models [23]. In the application of AUSM schemes to two-phase three-dimensional problems, we can mention the work of De Wilde et al. where a two-phase system composed of gas and solid particles was examined [24].

In 2006, Liou extended the AUSM-family schemes to the low-Mach number limit and employed this method (AUSM$^+$-up) to solve problems at different speeds [25]. This scheme improves over previous versions and eradicates fails found therein. Halder et al. used the AUSM$^+$ scheme to investigate supersonic wake of a wedge on an unstructured grid [26]. The developed unstructured Euler solver with AUSM$^+$ flux splitting scheme is capable enough to capture the oblique shock and expansion fans properly.

Only few methods can correctly simulate two-phase condensing flows in a complicated geometry such as turbine stages, because these flows experience spontaneous nucleation with sharp gradient regions. In the present paper, the AUSM-van Leer hybrid scheme is used to solve the governing equations of nucleating condensing two-phase flows in a steam turbine cascade. Then, effects of surface roughness on the performance of steam turbine blades are investigated in wet and dry cases. Also contribution of each of the loss mechanisms such as aerodynamic-,