
Perspectives on the Treatment of Secondary Flows in Axial Turbines

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Abstract

A review is presented of the main end-wall treatments for the secondary flows of axial turbines. This encompasses the use of axisymmetric and non-axisymmetric contoured end-walls, the use of fences, and of air injection and blowing. Experimental and numerical results show promise in all these techniques. Interest seems to be drawing towards the use of non-axisymmetric contoured end-walls, due to their good compatibility with current turbine passage designs and their appealing stage pressure loss reduction at design conditions and off design. An insight is provided into the flow changes from non-axisymmetric end walls and on their effect on secondary flow losses.

Keywords: axial turbines; secondary flows; endwall modifications.

1. Introduction

Performance loss in an axial turbine occurs through different flow mechanisms that generate profile loss, tip leakage loss, and end wall or secondary flow loss. An overview of these mechanisms is given by Denton [1]. This paper focusses on the secondary flow loss. These flows are most relevant to low aspect ratio blades, typically used in high-pressure turbines [2]. Understanding the physics and ability to predict the secondary flow structures is the first step to control and reduce the loss and further achieve an increase in turbine efficiency.

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In a high-pressure turbine stator passage, Gostelow et al. [3] showed that the interaction of the end wall boundary layer and the adverse pressure gradient from the blade potential pressure field generates a horseshoe vortex near the junction of the blade leading edge and the end wall. The horseshoe vortex left and right arms wrap around the blade pressure and suction sides. The pressure side arm is swept pitchwise by the pressure gradient from the blade pressure side to the blade suction side. Part way through the passage, the suction and pressure side arms combine into a passage vortex. This vortex grows in size and strength and becomes the main loss generator, contributing to about 15% of the aerodynamic loss in a stage.

There is therefore scope for modifying the development of the end-wall vortices to reduce the overall passage vortex loss. To this end, this paper presents a selective review of effective techniques for improving the performance of axial turbines by turbine end wall modifications.

2. Endwall modifications

2.1. End wall fences

To reduce secondary flow losses in a linear turbine cascade, Kumar and Govardhan [4] applied a streamwise end wall fence. The fence changes the end-wall flow as sketched in Fig. 1 (a). They optimized the fence geometry by performing numerical experiments. By introducing this fence, the exit flow angle deviation, secondary flow losses, and the magnitude and spanwise penetration of the passage vortex were reduced. Chung et al. [5] showed that a boundary layer fence in the turbine passage can reduce the aerodynamic losses. Kawai et al. [6] also showed that using end wall fences results in a considerable attenuation of secondary flows, an improvement of the flow quality entering downstream stages, and a 26% reduction in the total pressure loss.

2.2. Air injection or suction

Bloxham and Bons [7] tested blowing and suction in a low pressure turbine cascade that resulted in a reduced loss of up to 28%. 23% of this performance gain was required to power the flow control system. The flow was controlled either the removal of the boundary layer, by suction, or by near-wall flow redirection, as shown in Fig. 1 (b). Dhilipkumar [8] performed a computational investigation into injecting air through a cylindrical hole in the end wall of the nozzle guide vane. The effects of the secondary jet on the formation of the leading edge horseshoe vortex and the consequent the passage vortex were modelled. The results indicate that an appropriate selection of the secondary jet results in an weakening of the leading edge horseshoe vortex and delaying the migration of the passage vortex across the guide vanes.
2.3. Axisymmetric contouring of the end-wall

Dossena et al. [9] investigated the flow through a turbine nozzle guide vane cascade with non-linearly sloped axisymmetric contoured end walls. The comparison of results from contoured and flat end wall geometries showed a significant performance improvement by contouring the wall. This was not only achieved by lower secondary losses but also by a reduction in the profile losses.

Moser et al. [10] optimized the axisymmetric contoured shroud for a guide vane of a steam turbine stage. An evolutionary algorithm was used to drive the axial variation of the shroud radius. The numerical results indicated that the axisymmetric flow path profiling reduced the loss over a wide range of pressure ratios. Barigozzi et al. [11] reduced the overall loss of a linear cascade of turbine blades with a planar passage by 20% by contouring one of the passage end walls. Most of this reduction was attributed to a lower profile loss as there was a reduction in the secondary losses on the planar wall side but a corresponding increase on the contoured wall side.

2.4. Non-axisymmetric contouring

End wall profiling aims to reduce the aerodynamic losses or heat transfer rates by shaping the end walls of the turbine hub and casing. The shaping either accelerates the flow, which decreases the local static pressure, or decelerates the flow, which increases the static pressure, as shown schematically in the Fig. 2. This way, the end wall cross-passage flow can be reduced by altering the pitchwise pressure gradient to reduce the associated secondary flows [12].

A numerical simulation of a nozzle guide vane passage with a profiled hub was first performed by [14]. This changed the passage cross-flow, reducing the loss. Dunn et al. [15] modelled the unsteady flow and the performance of a 1.5 stage turbine test rig with a profiled rotor hub end-wall. Their results indicate that at the selected test conditions this flow does not warrant the added computational expense of an unsteady simulation, unless the nature of the flow is substantially more unsteady or transient boundary conditions ar e used. Hartland et al. [16] and Ingram, et al. [12] tested a non-axisymmetric end wall design on a linear cascade and obtained about a 24% reduction in the secondary flow loss. Brennan, et al. [13] and Harvey et al. [17] used non-axisymmetric contouring to obtain a one-third reduction in the end wall loss and a 0.59% increase in the stage efficiency in a high pressure turbine and a 0.9% efficiency increase in the low pressure turbine of the Rolls-Royce Trent 500 engine. Germain et al. [18] improved the efficiency of a one-and-half stage highly loaded axial flow turbine using non-axisymmetric end wall contouring that reduced the secondary losses and the mid-span flow losses. Schuepbach et al. [19] confirmed these efficiency improvements by a time-resolved experimental and numerical investigation of the flow. This highlighted the presence of reduced blade trailing edge shed vorticity in the contoured wall passage.

A detailed numerical and experimental investigation was performed by Poehler et al. [20] to determine the effects of non-axisymmetric stator end wall contouring on the isentropic efficiency of a turbine stage. The results showed an aerodynamic improvement in terms of efficiency and of the reduction in the secondary kinetic energy. Miyoshi et al. [21] developed numerically a non-axisymmetric contoured end-walls for the nozzle blades of an air turbine. The predicted reduction in secondary flow losses was confirmed by experiments with both a contoured hub and casing.
The area mass-averaged total pressure loss coefficient decreased by 27% in the numerical simulation and by 35% in experiment with respect to having axisymmetric end-walls.

How the end wall geometry is parametrized has a crucial importance in the design process. Harvey et al. [22] adopted beta-spline and Fourier series based curves in the axial and circumferential directions to define the profiled end wall shapes. They demonstrated a reduction in secondary flows, in the secondary kinetic energy, and in the blade row exit angle deviations. Germain et al. [18] and Turgut and Camcı [23] used a combination of a pitchwise shape function and a streamwise decay function that, when multiplied and scaled, define the contoured end-wall surfaces. Praisner et al. [24] argued that there were disadvantages in using shape functions to parametrize a contoured end wall. Simple shape functions, such as a sinusoidal curve, imply a preconceived notion of the resulting geometry. Praisner et al. [24] therefore proceeded to parametrize their geometry using two-dimensional cubic splines in the pitchwise and streamwise directions. This removed some of the restrictions from the prescribed shape of the guide curves used in the previous work.

The computer-based optimization of the shape-defining parameters is a key enabler of contoured end-wall designs. Sun et al. [25] used an optimization technique based on combining end wall profiling parametrization, global optimization, and aerodynamic performance evaluation methods, lowering secondary flow and profile losses. Tang et al. [26] optimized the end walls of a one-and-half stage high-work axial turbine using a multi-island genetic algorithm, achieving a 10.7% total pressure loss decrement across the first stator and an overall 0.4% stage efficiency increase.

A later study by Tang et al. [27] investigated the effects of these profiled end walls on the turbine unsteady flow field using unsteady simulations. The numerical results showed that the profiled end walls on the first stator not only reduce the losses from the secondary flows and trailing edge shed vorticity of the stator, but also improve the performance of the rotor. As a drawback, the profiled end wall of the rotor had almost no effect on the performance of the first stator and was predicted to introduce significant unsteady effects to the turbine as the fluctuations of the flow fields were predicted to become stronger over time. Na and Liu [28] optimised the non-axisymmetric contoured end walls for the hub and shroud of a high pressure turbine stator. The numerical results showed that the optimized non-axisymmetric end walls have merit in reducing the flow losses in the stator as indicated in Fig. 3 (a). However, Fig. 3 (b) shows that they also have drawbacks at the stator exit, where the flow angle becomes more non-uniform, so that the flow losses at the rotor exit were predicted to increase from changes in the rotor incidence angle. As a result, the turbine stage performance was not improved. Poehler et al. [29] studied numerically the effect of non-axisymmetric end walls and three-dimensional aerofoils on the secondary flows of a one-and-half axial turbine stage. A contoured end wall for the hub and shroud, a bowed profile stacking and a combination of both were applied to the first stator. In addition, a contoured end wall was developed for the hub of the unshrouded rotor. The stage efficiency was used as the target function to optimize all designs. The results from this global optimization showed an increase in the stator total pressure loss and in the secondary flow. However, these designs led to a more uniform exit flow angle distribution and thus a subsequent reduction of the rotor losses that over-compensated the higher stator losses. Part two of this paper [30] reported on the experimental validation of the numerical results. A good agreement was observed with the
numerical results as the mechanical efficiency increased as predicted. The experimental results also demonstrated that the new designs still work satisfactorily at off-design conditions.

More recent investigations adopted a more holistic design approach to end-wall contouring, including considerations of heat transfer, seal flow, and of off-design operations. Lynch et al. [31] and Puetz et al. [32] investigated the effect of using contoured end walls on the heat transfer characteristics, Cao et al. [33] and Gier et al. [34] studied their use in conjunction with three dimensional turbine blades, and Hu and Luo [35] considered their effect on the rim seal flow. Reising and Schiffer [36] optimized the stator end walls in a transonic compressor at several operating point. They found that, even though the shroud was optimized for off design conditions, it resulted in a 0.03% additional efficiency improvement at the design point.

Kadhim et al. [37] introduced a guide groove based technique for designing the non-axisymmetric casing of an axial turbine and tested it on a 1.5 stage turbine. They used an analytical surface definition method based on the Beta distribution function, which is able to provide an analytically smooth interface with the remainder of the passage geometry. They showed by numerical modelling that the groove affects the natural path of the secondary flow features, reducing the secondary flow interaction. They predicted a reduction in the total pressure loss coefficient with the application of the contoured casing, both at design and off-design.

3. Conclusion

The literature review presented in this paper on the design and performance of end wall treatments for axial turbines shows a breadth of approaches, including fences, mass injection and ejection, and contoured end walls. Each technique has merits and drawbacks. Fences have shown good promise in laboratory experiments. Their application to engines is not yet matured, possibly due to concerns about their integrity from a long-term exposure to the high-temperature flows. Suction and blowing enables the intermittent operation of the end wall treatment, as well the implementation of feedback control techniques. The main challenges for this technique are the handling of hot gasses through the aspiration slots and the additional cost of providing mass injection, for instance using flow bled from an upstream blade row. Axisymmetric end walls may have originally been designed for the use in highly loaded turbines with a substantial flow velocity increase through the passage. Modern turbines for power tend to use less aggressive flow expansions and peak Mach numbers, for efficiency, which may limit the pressure recovery that is achievable from using axial variations in the radius of the end walls.

Non-axisymmetric end wall contouring was found to be comparatively the more mature technology for axial turbines. They have shown good performance at design conditions and off-design. There is not yet consensus on the best design practice for non-axisymmetric end walls. Techniques implemented in industry use a significant number of design parameters requiring substantial computer-based optimization. The author has shown the promise of a design approach that is based on the natural path of the secondary flows that may alleviate the design effort, by lowering the number of free parameters and still delivering good performance.

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