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Effects of camberwise varying tip injection on loss and wake characteristics of a low pressure turbine blade

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ABSTRACT

This paper presents the results of an experimental study that investigates the effects of camberwise varying tip injection on the total pressure loss and wake flow characteristics downstream of a row of Low Pressure Turbine (LPT) blades. This injection technique involves spanwise jets at the tip that are issued from a series of holes distributed along the camber line. The injection from each hole is individually and separately controlled using a computer driven solenoid valve and therefore the flow injection geometrical pattern at the tip can be adjusted to any desired variation. Three different injection cases are investigated including triangular, reversed triangular and uniform injection patterns. Here, triangular and reversed triangular cases refer to discrete blowing from the blade tip in which the blowing velocity increases (triangular) or decreases (reverse triangular) linearly from the leading to trailing edge along the camber. For uniform injection, the injection velocity is kept constant for all injection holes. The total mass injection from the tip is kept the same for all injection cases. The experiments are conducted in a continuous-flow wind tunnel with a linear cascade test section and measurements involve Kiel probe traverses 0.5 axial chords downstream of the blades covering a region between 85% and 100% span as well as two-dimensional Particle Image Velocimetry (PIV) measurements on 50%, 85% and 95% spanwise planes. For all injection cases, results show that tip injection reduces the total pressure loss levels in general. Highest measured overall loss reduction occurs in the case of reversed-triangular injection. The least effective waveform is observed to be triangular injection. There is significant reduction in the extent of the low momentum zone of the leakage vortex with injection. This effect is much less pronounced for the passage vortex. On the other hand, complex flow patterns are observed within the passage vortex, especially in the case of reversed-triangular injection, such as a possible embedded vortical structure along the passage vortex core, which creates double peaks in the velocity and turbulent kinetic energy fields.

1. Introduction

In unshrouded low pressure turbines, the flow leaks from pressure side towards suction side at the blade tips creating losses in the passage and downstream of the blades. Tip leakage flows are highly three-dimensional and there exists complex flow structures interacting with each other. The physics of tip leakage flows is investigated by Bindon (1989). It was shown that there is no single flow pattern and the leakage mechanism is quite complex. In the front part of the tip gap, the inlet casing boundary layer enters the gap from the leading edge and then rolls-up into a vortex structure before approximately 30% chord location. In this region, there's no separation of the flow within the gap. However, further downstream a separation bubble followed by a reattachment zone occurs within the gap, especially for sharp-ended blades. Heyes and Hudson (1993) showed there exists a low-pressure region near the pressure side of the tip gap confirming the separation bubble. The flow above the bubble is named an "isentropic jet" in the same study essentially due to the fact that it was loss free. Yaras et al. (1989) and Sjolander and Cao (1995) have done velocity measurements within the gap for different gap heights. They showed that at the gap exit, flow velocity is high and has an oblique angle relative to the passage flow interacting with the mainstream. This interaction between the tip gap flow and the passage flow creates the leakage vortex within which the turbulence intensity is high. McCarter et al. (2001) showed that the fluid leakage is maximum where the suction pressure is lowest and pressure difference

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Nomenclature

b	blade span
C_p	total pressure loss coefficient
C_x	axial chord
h	blade height
LPT	Low Pressure Turbine
M_{inj}	injection mass flow rate
Ω_z	mean vorticity
P_i	inlet total pressure
P_L	measured local total pressure
$\overline{P}_{L,p}$	pitch averaged total pressure
q_i	inlet dynamic pressure
ρ	air density
t	Tip Gap Height
U_i	inlet velocity
V_{inj}	injection velocity
x	pitchwise coordinate (tangential)
y	spanwise coordinate
z	axial coordinate (orthonormal to x and y)

between the two surfaces of the blade is maximum. In turbine blades, high flow turning causes larger pitchwise pressure gradients, which makes the leakage in turbines stronger compared to compressor blades (Yamamoto, 1988). Typically, 1% tip clearance can cause an increase in stage losses by 1–3% (Booth, 1985). Also as the tip clearance gets bigger, leakage mass flow increases, leakage vortex occupies a larger zone and loss levels become significantly elevated (Bindon, 1987; Dishart and Moore, 1990; Moore et al., 1994; Sjolander, 1997; Tallman and Lakshminaravana, 2001). There are other vortical structures within a turbine passage in addition to the tip leakage vortex such as the passage vortex (Wiedner, 1994; Gregory-Smith, 1997). It is reported that turbulence levels within the passage vortex core are high and in general there is a strong interaction between the passage vortex and leakage vortex starting from the downstream part of the gap (Xiao et al., 2001). Many other features of the secondary flow characteristics as well as tip leakage flows are investigated in detail by many previous researchers (e.g. Sieverding, 1985; Langston, 2000). The tip leakage is also significantly affected due to rotational effects. The relative motion of the casing creates complex velocity profiles with inflection points and shear regions within the tip gap (Dey and Camci, 2004), gap mass flow rate is observed to be reduced (Yaras and Sjolander, 1992a), blade tip surface pressure field is found to be less distorted and the strength of the tip vortex gets reduced as the relative casing wall speed increases (Yaras et al., 1992b).

As to controlling the tip leakage in turbine blades, several different methods were investigated in previous studies. Dey and Camci (2001) used tip platform extensions, structures like winglets, to control the tip leakage flow as well as partial squealer rims in a rotating turbine rig (Kavurmacioglu et al., 2007a,b). They conclude that suction side extensions only change the location of the leakage vortex but do not change the pressure loss within the vortex. They also noted that pressure side extensions are highly efficient to reduce the pressure loss and this extension type also reduces the momentum that leaks to the suction side. Zhou et al. (2012) also used winglets to control the leakage vortices. Van Ness et al. (2008) examined squealer tips as a control mechanism and investigated that the leakage mass flow and size of the tip leakage vortex reduces. Also the size of the casing separation bubble is decreased. They also used plasma actuators to control the leakage flow and noted that the strength of the clearance flow is weakened. In other studies such as (Heyes et al., 1992; Lee and Chae, 2008; Lee et al., 2011) squealer rims are used. In these studies, it is noted that as squealer rim height increases, leakage vortex strength and total pressure loss are decreased. It is reported that suction side squealer rims have more benefit on decreasing total loss compared to pressure side rims. Rao and Camci (2004) injected air through coolant holes at the tip and observed a reduction in total pressure loss within the vortex. The size of the leakage vortex was also reduced. Niu and Zang (2011) also reported similar results for tip injection. Behr et al. (2008) investigated casing injection to control the leakage flow. They indicated that injection increased aerodynamic performance and decreased turbulence levels. Also they showed that injection from aft region of the gap has an effect on passage vortex, whereas injection from middle region of the gap has an effect on leakage vortex zone.

This paper presents the results of an experimental study that investigates the effects of camberwise varying tip injection on the total pressure loss and wake flow characteristics downstream of a row of Low Pressure Turbine (LPT) blades. This injection technique involves spanwise jets at the tip that are issued from a series of holes distributed along the camberline. The injection from each hole is individually and separately controlled using a computer driven solenoid valve and therefore the flow injection geometrical pattern at the tip can be adjusted to any desired variation. Three different injection cases are investigated including triangular, reversed triangular and uniform injection patterns. Here, triangular and reversed triangular cases refer to discrete blowing from the blade tip in which the blowing velocity increases (triangular) or decreases (reverse triangular) linearly from the leading to trailing edge along the camber. The experiments are conducted in a continuous-flow wind tunnel with a linear cascade test section and measurements involve Kiel probe traverses 0.5 axial chords downstream of the blades covering a region between 85% to 100% span as well as two-dimensional Particle Image Velocimetry (PIV) measurements on 50%, 85% and 95% spanwise planes.

2. Experimental setup and measurement details

2.1. Cascade facility

The experiments are performed in a continuous-flow wind tunnel with a linear cascade test section that consists of a 0.6 m diameter double-intake radial blower driven by a frequency controlled 18.5 kW AC electric motor, a 2.6 m long rectangular to square transitional diffuser with a 7 deg diffusion angle, a 1.85 m long $1.1 \times 1.1\ \mathrm{m}^2$ square cross-section settling chamber with multiple screens, a 0.915 m long contraction with an area ratio of 3.36 followed by a 0.5 m long square-to-rectangular transition duct. The linear cascade test section is placed at the exit of this transition duct.

The fully transparent cascade test section shown in Fig. 1a is made out of 0.01 m thick acrylic and it consists of a single row of LPT blades with T106 blade profiles. This is an ultra-high-lift profile with a Zweifel coefficient of 1.2. More details and coordinates of the profile can be found in Stieger (2002) and Zhang (2005). There are five blades in the cascade each with a chord of 0.15 m and a total turning angle of 100°. The number of blades is selected