International Journal of Heat and Fluid Flow 56 (2015) 335–343

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

An experimental and computational study of tip clearance effects on a transonic turbine stage

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ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 20 August 2015
Accepted 17 September 2015
Available online 30 October 2015

Keywords:
Tip leakage flow
Heat transfer
Transonic turbine

ABSTRACT

This paper describes an experimental and computational investigation into the influence of tip clearance on the blade tip heat load of a high-pressure (HP) turbine stage. Experiments were performed in the Oxford Rotor facility which is a $1\frac{1}{2}$ stage, shroudless, transonic, high pressure turbine. The experiments were conducted at an engine representative Mach number and Reynolds number. Rotating frame instrumentation was used to capture both aerodynamic and heat flux data within the rotor blade row. Two rotor blade tip clearances were tested (1.5% and 1.0% of blade span). The experiments were compared with computational fluid dynamics (CFD) predictions made using a steady Reynolds-averaged Navier–Stokes (RANS) solver. The experiments and computational predictions were in good agreement. The blade tip heat transfer was observed to increase with reduced tip gap in both the CFD and the experiment. The augmentation of tip heat load at smaller clearances was found to be due to the ingestion of high relative total temperature fluid near the casing, generated through casing shear.

1. Introduction

Turbine blade tips are difficult to cool and, due to their immersion in hot gases, they are susceptible to thermal degradation. A large number of studies have investigated the nature of heat transfer to turbine blade tips. However only a small subset of those studies have performed experiments at fully engine representative flow conditions due to the complexities of rotating-frame testing at engine-scale Mach and Reynolds numbers. The majority of the experiments that have been reported to date have been performed in stationary cascades. At low speed, the heat transfer distribution is dominated by separation of fluid from the pressure side tip gap corner and its possible subsequent reattachment (see for instance Newton et al., 2006; Palafox et al., 2006; Lee et al., 2009).

Newton et al. (2006) used a low speed linear cascade, without relative casing motion, to obtain heat transfer coefficient distributions on the flat tip of a generic turbine blade in a five blade linear cascade. From the two tip gaps (1.6% and 2.8% of blade chord) that were tested it was evident that with the larger clearance gap the region of separation increased. The maximum heat transfer coefficient occurred in the region of reattachment on the blade tip — essentially along a line parallel to the pressure side corner. This region was more extensive for the larger tip gap, though the peak heat transfer coefficient values were similar.

Palafox et al. (2006) made similar observations at tip clearances of 1%, 1.5% and 3% of blade chord in a low speed linear cascade; for each tip gap there was a thin region, between mid-chord and the trailing edge, of high Nusselt numbers parallel to the pressure side tip gap corner. As the tip gap was reduced, the high Nusselt number region moved towards the pressure surface and (in contrast to some other studies, a number of which are discussed below) the Nusselt numbers increased. This trend was the same both with, and without, relative over-tip casing motion. Blade tip static pressure measurements and two-dimensional particle image velocimetry of flow within the tip gap revealed that the high Nusselt number region was associated with the reattachment of the flow that had separated off the sharp pressure side tip gap corner.

Several studies have demonstrated that the flow within the tip gap of a transonic turbine is itself transonic (Moore et al., 1989; Moore and Elward, 1993; Thorpe et al., 2007). Numerical simulations and experiments that have reproduced such conditions (by, for instance, using high speed linear cascades) have shown that as well as the separation and subsequent reattachment observed at low speed, blade tip heat transfer distributions may be significantly altered by changes of adiabatic wall temperature and by the reflection of shock waves from the blade tip (Wheeler et al., 2011; Shyam et al., 2010; Zhang et al., 2011a,b). These effects

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2015.09.001
0142-727X/

Nomenclature

C_{ax}	axial chord
C_f	skin friction coefficient
c_P	specific heat capacity at constant pressure
g	tip gap height
h	heat transfer coefficient
M	Mach number
$\dot{m}$	mass flow rate
P	pressure
$\dot{q}$	surface heat transfer rate per unit area
T	temperature
U	casing velocity
V	tip flow velocity
x	tip gap width
ρ	density
τ_w	wall shear stress

Subscripts

LG	large gap
1	stage inlet
2	NGV exit
aw	adiabatic wall
o	stagnation quantity
rel	relative quantity
w	wall

may be expected to affect how the heat transfer distributions change when the tip gap is reduced.

Bunker et al. (2000) measured heat transfer coefficient distributions on a flat blade tip downstream of a casing step in a linear cascade with an exit Mach number of 0.75. Decreasing the tip clearance by 37% (from the nominal tip clearance of 2.0% of blade span) resulted in approximately a 10% decrease of heat transfer coefficient, while an equivalent increase of tip clearance resulted in a 10% increase of heat transfer coefficient.

Azad et al. (2000a,b) made heat transfer measurements on a flat blade tip and recessed tip with tip gaps of 1.0%, 1.5% and 2.5% of blade span in a linear cascade with an exit Mach number of 0.59. It was concluded that generally a larger tip gap resulted in a higher heat transfer coefficient.

Similarly, Nasir et al. (2004) detailed heat transfer coefficient distributions on the tip surface of flat and recessed high pressure turbine blade tips in a linear cascade with an exit Mach number of 0.54. The plain tip exhibited relatively low heat transfer coefficients downstream of the leading edge for both tip gap sizes (1.0% and 2.6% of span) due to the low pressure gradient across this area. Flow separation occurred at the pressure side blade tip corner as the flow entered the tip gap and then reattached on the tip surface causing a low heat transfer region immediately downstream of the corner and high heat transfer in the reattachment region. Lower heat transfer coefficients were measured for the smaller tip gap height (1.0% of blade span) and this was said to be due to the fact that there was less leakage flow over the blade tip than with the larger tip gap (2.6% of blade span). The enhanced heat load for the larger clearance gap was also attributed to the larger tip gap Reynolds number.

There have also been several studies of blade tip heat transfer made using high speed rotating rigs which more closely simulate the flow conditions found in operational gas turbines (Bunker, 2001). One such example is the study reported by Metzger et al. (1991) who measured blade tip heat transfer rates at five locations that were distributed along the tip between about 5% and 30% of chord. The measurements were performed using miniature platinum thin-film gauges at two different tip gaps (0.38 mm and 0.64 mm) using a high speed, rotating, single stage turbine. The results showed an increase of local heat flux of approximately 30% at about 30% of blade chord when the tip gap was increased.

Dunn et al. (1984b) reported the results of heat flux measurements made on a turbine blade and casing in a high speed full stage rotating turbine. The tip gap was reported to be 0.3 mm when the turbine was operating at 27,000 rpm (Dunn et al., 1984a). Ameri and Steinthorsson (1996) modelled the experiment reported in Dunn et al. (1984b) using a code which solved the Reynolds-averaged Navier–Stokes (RANS) equations. This paper is of additional interest because it was reported that the casing and tip measurements were actually conducted for two tip gap heights; 1.11% and 1.85% of span at the location of the blade leading edge at the hub (only results from one tip gap height were reported in Dunn et al., 1984b). A comparison of the predicted blade tip Stanton number contours (based on inlet conditions and therefore proportional to local heat flux) for the two gap sizes revealed a general decline in levels with increasing tip gap size. This was in agreement with the experimental data which, over the first 30% of the blade axial chord at the tip, also showed a lower Stanton number when the tip gap was increased. This trend contrasts with many of the cascade based investigations of which some were mentioned previously.

Ameri et al. (1999) performed a numerical study (using a RANS solver and a $k-\omega$ turbulence model without wall functions) of the effects of tip gap height and casing recesses on heat transfer and stage efficiency in a high speed axial turbine. Tip gap heights of 0%, 1%, 1.5%, and 3% of the passage height were modelled. For the two largest tip gap heights considered, different casing recess depths were studied. The results from the plain casing tests showed that larger tip gap heights increased the predicted Stanton numbers (based on inlet conditions) over the forward half of the blade tip. The converse was true for the aft half of the blade tip. The reason for this was concluded to be that as the clearance was increased the velocity over the upstream portion of the blade tip increased resulting in an increase of heat transfer to the blade tip. The heat transfer to the downstream portion of the blade tip was mostly dominated by the size and the extent of the separation bubble; as the gap was increased there was a larger portion of the blade tip over which the flow was unattached. This led to smaller heat transfer rates to the downstream portion of the blade tip. Nevertheless it was stated that an increase in the thermal load on all the heat transfer surfaces considered was observed due to enlargement of the tip gap.

The effects of endwall motion have been studied predominantly computationally, and tend to show a reduction in over-tip leakage and reduction in heat load (Krishnababu et al., 2007; Tallman and Lakshminarayana, 2001). Recent work such as Zhou et al. (2012), showed that both the tip flow aerodynamics and heat flux distribution change significantly with the introduction of a moving endwall. Coull and Atkins (2013) showed recently that the combined effects of a moving casing, and realistic inlet boundary layers and secondary flows entering the rotor passage have a much greater influence on the tip flow and heat transfer than would result from a simple addition of these effects. That is to say that there is a strong coupling between the development of the secondary flows and the endwall motion which has a large influence on the blade tip.