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FLOW AND HEAT TRANSFER ON AND NEAR A TRANSONIC TURBINE BLADE TIP

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ABSTRACT

The flow over a HP turbine blade tip is one of those most complex in turbomachinery. The blade tip is also one of the most vulnerable components within a turbine blade, due to its high thermal load and difficulty to cool. Considerable research on blade tips has been undertaken in the last twenty years. However, there are only very limited data in the literature on blade tip heat transfer in a transonic environment, i.e., for blade exit Mach numbers >1. Flow and heat transfer measurements can of course more easily conducted at a low speed condition, as often been done. These low speed tests can provide useful information for basis understanding and validation of predictive capabilities. However, their values will have to depend on the extent and nature of the differences in over tip flow and heat transfer behavior between an engine representative transonic flow and a low speed subsonic one. At engine conditions, it is still not well understood how much of the turbine tip flow is transonic and hence what effect this has on tip heat transfer and aerodynamics.

The main objective of the present work is to identify and understand the governing flow mechanisms in the HP turbine blade tip heat transfer at engine representative transonic conditions. A detailed spatially-resolved experimental heat transfer measurement on a transonic turbine blade tip has been conducted. The experimental results are then used to assess and validate an advanced CFD tool. And furthermore the detailed CFD results are explored to elaborate and understand the experimentally observed phenomena.

Experimental study

The experiments are conducted using the transient infrared thermography technique within the new Oxford High Speed Linear Cascade research facility in the Osney Laboratory, the University of Oxford. A PID feedback control system enable a steady flow at the inlet of the test section during every blowdown test. A relatively constant total pressure of 200kpa (absolute) can be maintained for about 90 seconds. The test section includes 4 passages and 5 blades (including two sidewalls representing a suction side and a pressure side). A Zinc-Selenide window is placed on the top casing wall, so that the central test blade tip surface is accessible to an infrared camera (FLIR A320) for spatially-resolved surface temperature measurements, as shown in Fig. 1. The blade tip surface is made of epoxy with very low thermal conductivity. In-situ calibration has been conducted by placing thermocouples on the blade tip with the IR window in place.

Experimentally measured heat transfer coefficient (htc) and adiabatic wall temperature for the blade tip with a tip gap clearance of 1.3% (gap versus span) are presented. These results have a major difference compared with other flat tip heat transfer data in the disclosed literature (mostly low Mach number).

(1) The heat transfer coefficients in the first half of the blade tip are substantially higher than in the second half. No such "sweet spot" (reported by Bunker et al. [1] and others) is observed. Especially, near the leading edge region, the heat transfer coefficients are roughly 70% higher than the average.
(2) A stripe of low heat transfer coefficient region is observed in the region of the pressure side separation bubble. There is also a band of low heat transfer coefficients around the middle of the tip surface, normal to the flow direction. In a low speed test, Newton et al. [2] reported that the maximum heat transfer coefficient occurs in the region of reattachment on the blade tip essentially along a line parallel to the pressure-side rim. This doesn't exist in the present study.
(3) Interestingly, a small region of high heat transfer coefficients locates close to the trailing-edge, which in the engine environment will be very difficult to cool.

Experimental results from other tip gap clearances also shows consistent data trend. Interesting stripes and variations of temperature field are observed on the tip surface. These different observations between the present study and previous literature (mostly low speed) should be linked to tip flow structure changes. Further interpretation of the heat transfer results at hands needs more understanding of the flow field above the blade tip under the current transonic flow condition, which leads to the CFD virtual experiment efforts described in the next part of this paper.

Numerical Predictions

Rolls-Royce HYDRA/PADRAM suite is employed in the present numerical predictions. The core of the software is a preconditioned Runge-Kutta solver of the discrete Euler or Reynolds-averaged Navier-Stokes equations (RANS). In this paper, steady calculations are performed and the Spalart-Allmaras (SA) turbulence model is implemented. The computational domain consists of one blade with periodic boundary conditions. The blade definition, tip gap clearance, flow angle, and inlet boundary conditions are kept exactly same as the experimental setup. Grid sensitivity studies are conducted to make sure that the mesh employed is grid independent in terms of heat flux. Visualization of the Hydra solutions has been done using the commercial FieldView software package.

The Mach number distribution (determined by local total and static pressures) along a cut plane in the middle of the tip gap clearance is presented in Fig. 2. The peak Mach number in the tip gap flow is about 1.9. The dark blue contour lines indicate locations for Mach=1. Apparently, apart from the leading edge region, the majority of the blade tip experiences supersonic flow.

The CFD results give good agreement with the experimental heat transfer data. Largely similar trends and spatial variations of heat flux are observed at similar locations on the tip numerically and experimentally.

Four cut planes are made on the blade tip surface along leakage flow streamlines direction, as shown in Figure 3. In this contour plot, heat flux distribution is still shown on the blade tip surface by grayscale, white color indicates a higher heat flux and black color means a lower heat flux. Mach number distributions are presented for the four cut planes in color. Clearly the variations of heat flux correspond to those flow features associated the shock system. The stripes in the heat flux contour are linked to shock waves reflected within the tip gaps. Near the pressure side corner, the flow accelerates and an oblique shock wave originates near the separation bubble. This is observed from all four cut planes. Compared with typical low speed data from the literature, the separation bubble size at the present transonic condition is much smaller due to the existence of shock waves. The results here are consistent with compressible sharp-edged orifice flow calculations found in the literature and with the theory of oblique shock wave formation in supersonic flow over a wedge. For the cut plane 1, the flow continues to accelerate after the first reflection of the oblique shock wave between the casing and the tip. A normal shock wave is generated immediately afterwards. Cut planes 2, 3 and 4 show more reflections of the oblique shock waves between the casing and the tip surface. The boundary layer thickness is greatly changed by the shock-boundary layer interaction. A thinner boundary layer thickness is observed after the oblique shock foot, due the local acceleration in the supersonic flow. And the accelerated viscous layer in this accelerated supersonic flow leads to an enhancement of heat transfer.

Therefore, shock waves in the tip leakage flow clearly influence the surface heat transfer distributions, leading to higher blade temperatures at certain regions.

Conclusions

The experimental and numerical results reveal the underlined complex transonic flow structures, and the associated over tip heat transfer characteristics.

The major conclusions are:
1.The majority of the blade tip (apart from the leading edge region) experiences a transonic flow with a peak Mach number of 1.9.
2.The large variations in flow speeds from low-speed subsonic flow to high speed supersonic flow in the tip gap give rise to significantly different heat loads over the tip. The heat transfer in the subsonic region is significantly higher than that in the transonic counterpart.
3.There is a clear heat transfer signature (heat flux stripe) of shock waves in the tip gap. An oblique shock wave initiates around the pressure side edge, and then reflects between the casing and the tip. A normal shock wave is generated before the leakage flow exits the tip. The resulting normal shock-boundary layer interactions contribute to further enhancements of heat transfer to the blade tip near the shock foot.
4.The CFD solver is able to capture most of the spatial heat flux variations and gives prediction results which compare well with the experimental data.

The results presented in this paper suggest that any cooling scheme must take into account the transonic nature of the tip flow in order to avoid large spatial gradients in blade temperature.

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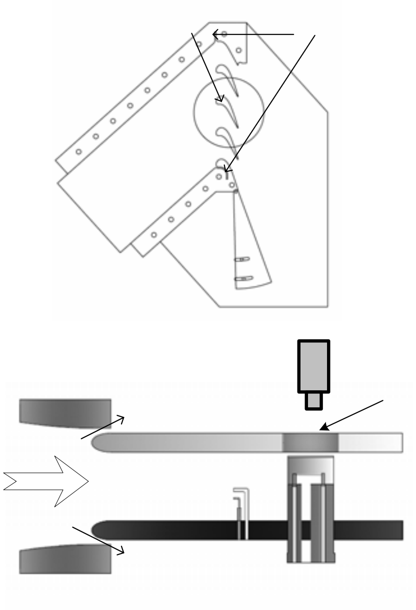

Figure 1. The schematic of the test section.

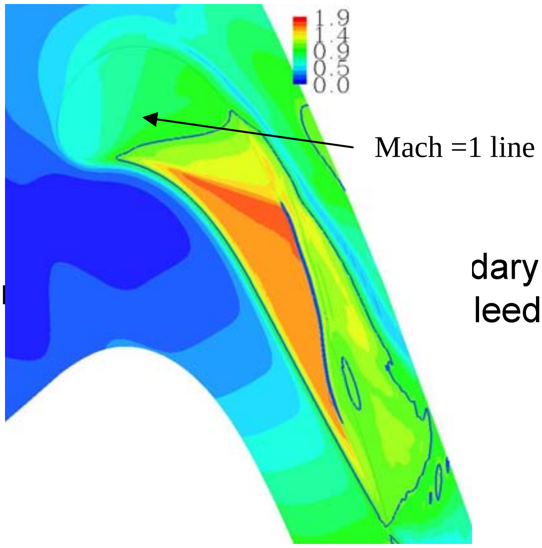

Figure 2. Local Mach number distribution along a cut plane in the middle of the tip gap clearance.

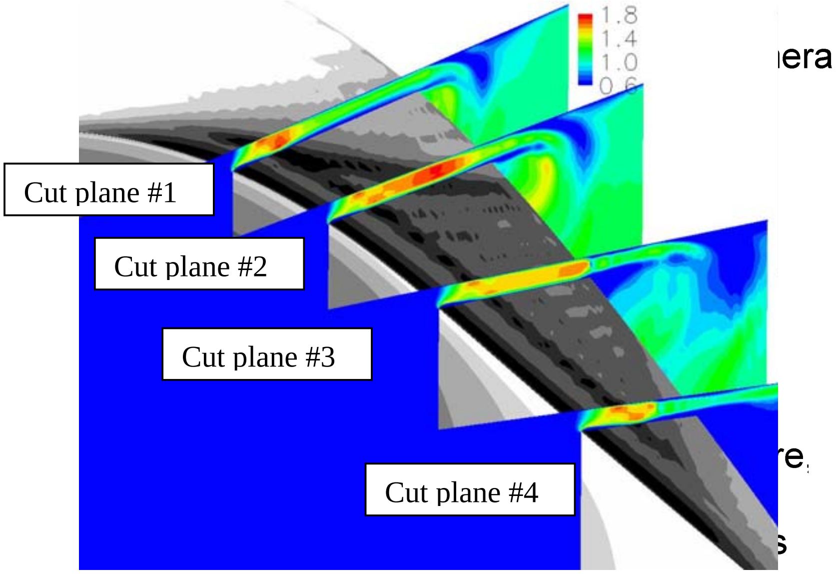

Figure 3. Tip surface heat flux and tip gap Mach number distributions, for a tip gap clearance of 1.3%.