A REVIEW OF TURBINE BLADE TIP HEAT TRANSFER

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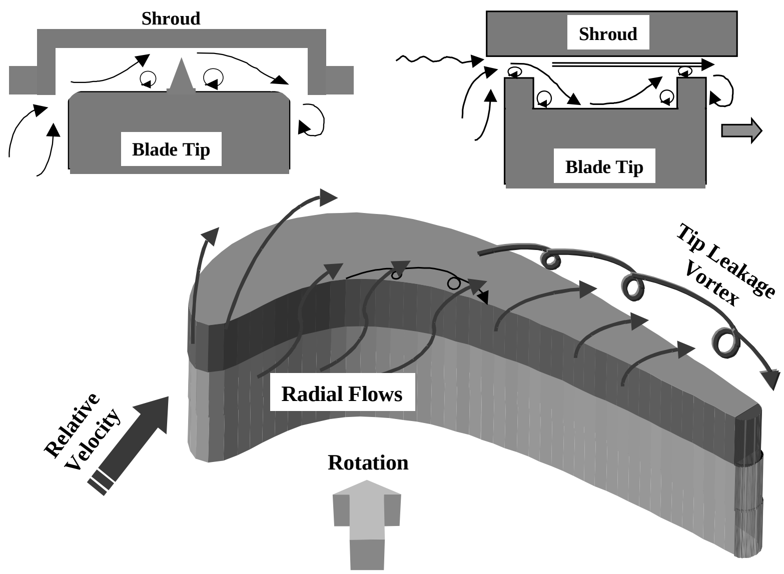
This paper presents a review of the publicly available knowledge base concerning turbine blade tip heat transfer, from the early fundamental research[1-5] which laid the foundations of our knowledge, to current experimental and numerical studies utilizing engine-scaled blade cascades and turbine rigs[6,7]. Focus is placed on high-pressure, high-temperature axial-turbine blade tips, which are prevalent in the majority of today's aircraft engines and power generating turbines.

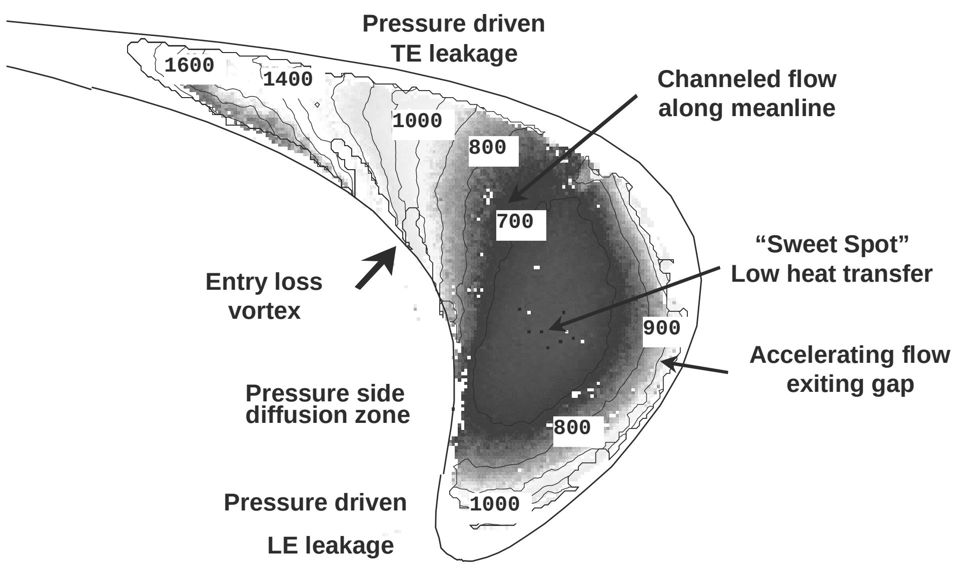
The design of high efficiency, highly cooled gas turbines is achieved through the orchestrated combination of aerodynamics, heat transfer, mechanical strength and durability, and material capabilities into a balanced operating unit. While decades of research have been dedicated to the study and development of efficient aerodynamics and cooling techniques for turbine airfoils, there remain regions, which retain a somewhat more uncertain design aspect, requiring more frequent inspection and repair. One such region particular to high-pressure turbines is the blade tip area. Blade tips are comprised of extended surfaces at the furthest radial position of the rotating blade, which are exposed to hot gases on all sides, typically difficult to cool, and subjected to the potential for wear against the outer shroud flow path. The blade tip operates in the transitional environment between the rotating airfoil and the stationary flow path casing, which experiences the extremes in most fluid-thermal conditions within the turbine.

The cooled turbine blades found in today's modern gas turbine engines represent very complex heat exchangers of specific aerodynamic shape and strict structural integrity. The blade tip region is arguably the most three-dimensional portion of the blade in terms of hot gas flow interaction, coolant delivery, and geometry. Issues which challenge the best turbine designers include:

- The blade tip is subjected to extremes in convective heat transfer loads.
- An extremely complex flow with periodic unsteadiness and leakage flows.
- Combustion systems can impose severe radial gas temperature profiles.
- Hot gas temperature and pressure variations as operating conditions change.
- Blade tip thermal gradients can result in high thermal stresses and cracking.
- The loss of tip material alters the flow field and thermal conditions over time.
- Aerodynamic and thermal boundary conditions change during short transients.
- Blade tip weight directly impacts the blade root stresses, LCF life, and creep.
- Increased blade tip cooling represents a chargeable flow penalty on the cycle.
- Film cooling adds further complexity or constraints in many factors.



Schematic Representation of Time-Averaged Blade Tip Flows



Detailed Heat Transfer Coefficient Distribution for Smooth, Flat Blade Tip Cascade Model[6], W/m2/K (Reproduced with permission from the Transactions of the ASME).

Our understanding of turbine blade tip heat transfer today is certainly far beyond the fundamental level of knowledge initiated nearly twenty years ago. In truth however, our ability to correctly perform pre-service blade tip designs rests primarily on our engine experience. The pace of technology advancement in high-temperature turbines has outstripped our investigation of the complex thermal conditions in blade tip regions. While we have concentrated more efforts on the fundamentals of airfoil heat transfer and film cooling, blade tips have advanced through invention and testing. We are at a point now when CFD heat transfer predictions are becoming very attractive and cost effective means for designing blade tips, but this still requires closure of the ever present turbulence modeling issue. Though methods such as Large Eddy Simulation may help to bridge the CFD needs, there still remain many areas requiring research and development to allow a full understanding of turbine blade tips. To date, we have only engine experience to describe the effects of tip film coolant mixing fundamentals, both on blade tips as well as on the airfoil surfaces near the tip. Our knowledge of the effects of unsteadiness on tip heat loads is very limited at this time, covering only a few discrete locations in some uncooled rig tests. There are as yet no reported studies on heat transfer for blade tips utilizing attached shrouds. The ability to predict blade tip heat transfer also rests on a better understanding of the hot gas migration and temperature profiles present in the many types of combustion-turbine systems. The understanding of how heat transfer coefficients and film effectiveness change as the blade tip are altered in service is a wholly unexplored area. As such information becomes more plentiful, innovative solutions will be required to extend blade tip life.

The state of our current understanding of turbine blade tip heat transfer is in the transitional phase between fundamentals supported by engine-based experience, and the ability to *a priori* correctly predict and efficiently design blade tips for engine service.

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