Chapter 1
Introduction

Secondary flows have become increasingly significant in the design of modern gas turbines due to several fundamental trends in gas turbine engine development. These trends include: increasing turbine inlet temperature, decreasing blade aspect ratio (S/C), and increasing cooling flows to the turbine vanes and blades. Each of these trends dramatically affects the life and durability of an engine hot section, increasing the importance of understanding the secondary flows that arise in turbine vane and blade passages.

The term secondary flows refers to the three-dimensional, vortical flow structures that develop in turbine vane and blade passages due to high turning of the flow and non-uniform inlet total pressure profiles. These vortical flows manifest themselves primarily in the endwall regions of the passage, where steep gradients in flow velocity and fluid properties exist. Deviations of flow angle from that predicted by two-dimensional flow analysis define and indicate the presence of secondary flows. These deviations in flow angle are three-dimensional, as secondary flows are three-dimensional in nature. Thus, the flow field through a turbine passage can be thought of as the superposition of a primary two-dimensional flow and the three-dimensional secondary flow.

A simple argument regarding the origin of turbine passage secondary flows is presented by Lakshminarayana (1996) and is illustrated in Figure 1.1. Lakshminarayana approaches the topic from the perspective of inviscid flow theory to show the effects of radial velocity and temperature distributions on turbine passage flow. By considering two different streamlines passing through a turbine, one originating in the inviscid freestream and the other in the velocity boundary layer, the development of secondary flows is explained. Assuming that the cross passage pressure gradient imposed on both streamlines is the same, and knowing that this pressure gradient must be balanced by the centripetal acceleration of a fluid particle traveling along each streamline, it is shown that the radius of curvature of the streamline originating in the boundary layer must be less than that of the mainstream streamline. This deviation in flow path indicates the formation of turbine passage secondary flows. Though this argument explains secondary flow development within a turbine passage, it does not explain all aspects of secondary flows as observed experimentally. A more complete discussion of secondary flows, including explanation of their development and presentation of secondary flow models as proposed by several independent researchers, is given in Chapter 2.

1.1 Impact of Secondary Flows on Gas Turbine Performance

Driven to achieve higher engine efficiencies, the gas turbine industry is continually increasing both compressor pressure ratio and turbine inlet temperature. Though cycle efficiency is only a function of pressure ratio for an ideal simple cycle, this is not the case for realistic engine cycles. When component losses are taken into consideration, cycle efficiency is found to depend upon turbine inlet temperature as well. This dependence is clearly illustrated in Figure 1.2 for typical values of compressor and turbine polytropic efficiencies. The reason that cycle efficiency increases with turbine inlet temperature is that the ratio of turbine power output to compressor power input increases and component losses become relatively less important. However, the increase in cycle efficiency with turbine inlet temperature is not without bound. When the inlet temperature becomes exceedingly high, requiring the use of aggressive active cooling schemes to maintain suitable turbine component temperatures, efficiency gains become marginal due to the additional losses introduced by such cooling. In effect, this situation is one of diminishing return. Beyond a certain limit, further increases in turbine inlet temperature will actually result in decreasing cycle efficiency, as the losses associated with cooling become overwhelming. This turbine inlet temperature limit is indicative of the state of material and cooling technology and will invariably increase with the maturation of such technologies.

For military aircraft applications, however, the motivation for increasing turbine inlet temperature is to maximize another engine performance parameter known as specific thrust. Specific thrust is defined as the thrust output per unit mass flow through the engine. Unlike cycle efficiency, specific thrust continues to increase with turbine inlet temperature. The benefit of an increase in specific thrust can be realized in two ways. In the design of a new engine, an increase in specific thrust capability enables a reduction of engine size and weight to achieve a given thrust output. For existing engines, an increase in specific thrust capability simply translates into more thrust output.

Since new engine development is expensive, growth versions of existing engines are often pursued whereby turbine inlet temperature is increased and advanced cooling concepts are employed. This approach allows for substantial increases in engine output without a complete redesign of the turbomachinery. Figure 1.3 illustrates the potential increases in specific core power with increasing turbine inlet temperature up to the hydrocarbon fuel stoichiometric limit. Since the inception of the gas turbine engine, advances in technology have increased specific power output by more than a factor of 4. Despite these tremendous advances, the potential still exists to further increase the specific power output to more than three times the level of engines today.

In the early years of gas turbine engine development, the aspect ratio of turbine blading was significantly higher than that which is typical today. This was primarily due to the lack of sophisticated design tools capable of handling three-dimensional flow effects in the hub and tip regions. To meet design goals with the design tools available at the time, the impact of these three-dimensional flows had to be minimized. This was accomplished through the use of higher aspect ratio blading. Today, with advancements in design tools and computational fluid dynamics, the flow field through complex, three-dimensional, low aspect ratio blading can be predicted with reasonable accuracy and modifications can be made to improve the design prior to more costly testing. The trend toward lower aspect ratio blading is primarily driven by improved vibratory characteristics and increased aerodynamic loading capability, yielding higher turbine work output per stage. However, with low aspect ratio blading, secondary flows dominate the flow field and account for a large portion of the overall total pressure loss incurred across a component. Additionally, secondary flows make film cooling difficult as the vortical action of these flows scour component surfaces, removing valuable coolant. Finally, secondary flows can alter exit flow angles substantially. If the designer does not account for these changes in the design of downstream components, aerodynamic mismatch will result in poor turbine performance. Despite these drawbacks, the trend toward lower aspect ratio continues, aided by improvements in the available computational tools.

As turbine inlet temperature continues to increase, so do the cooling air requirements of the turbine. With inlet temperatures well above the melting temperature of turbine components, as much as 20 to 30% of the core flow bypasses the combustor to serve as coolant. The objective in the design of cooled vanes and blades is to minimize the amount of cooling flow necessary to adequately cool the part, as these flows introduce additional aerodynamic loss. Reductions in cooling flow requirements are achieved through the development of advanced cooling concepts. Figure 1.4 shows the progression of turbine cooling technology over time, from early uncooled turbines to advanced impingement and film cooled parts. To achieve higher turbine inlet temperatures and engine specific power output, advances in cooling technology are essential.

With these trends in mind, it is instructive to consider their impact on turbine component life. First, the trend of increasing turbine inlet temperature directly presents a more severe environment in which the turbine must survive, and explains the last trend of increasing cooling flows. However, secondary flows make cooling of the passage endwall and vane or blade surface exceedingly difficult, as they entrain near wall fluid, sweeping cooling flow from the surfaces. The trend of lower aspect ratio blading further exacerbates the problem. With lower aspect ratio blading, the secondary flows occupy a larger portion of the blade span, and thus entrain hotter combustion gases that reside toward the passage midspan. In summary, secondary flows act in three ways that are detrimental to turbine life. First, they sweep near wall fluid, including expensive film cooling air, away from the endwall and into the vane or blade passage freestream. Second, they transport higher temperature freestream fluid to the endwall, thus increasing the driving potential for heat transfer. Finally, secondary flows increase the convective heat transfer coefficient on the endwall.

1.2 Research Approach and Uniqueness

Many researchers have worked to gain an understanding of secondary flow development and the impact of such flows on turbine heat transfer. However, few have pursued ways to mitigate the detrimental effects on turbine heat transfer. Most secondary flow reduction studies have focused on the aerodynamic benefit. Unlike these studies, the objective of this research effort was to reduce the severity of the thermal environment in which the turbine must survive by altering the turbine passage secondary flows. This was accomplished through geometrical changes to the vane by applying a leading edge fillet. Specifically, this objective was pursued through optimization of a leading edge fillet that reduces the strength and dominance of secondary flows in a vane passage, and thereby reduces the adverse effects of their presence. The benefits of the resulting fillet design are a reduction in film cooling flow necessary to maintain suitable component temperature and/or an increase in turbine life. Another important distinction of this investigation from past research is the use of more realistic combustor exit total pressure profiles for the inlet condition to the vane cascade. Most past studies of turbine passage secondary flows and heat transfer have assumed a two-dimensional turbulent boundary layer inlet condition, which does not accurately represent the flow field exiting a combustor. To achieve more realistic inlet conditions, a combustor simulator was utilized in this investigation that mimics the fluid mechanics of a typical aircraft engine combustor.

The approach of this research was to employ a commercial optimization software package in conjunction with a computational fluid dynamics package in the design of a turbine vane leading edge fillet. The objective was to minimize the severity of the thermal environment in which the vane and endwall must survive through modification of the secondary flows. Following the optimization process, the resulting fillet geometry was tested in a large-scale turbine vane cascade to verify its performance. Details of the optimization and computational approach are discussed in Chapter 3, while the experimental facility and measurement techniques employed for fillet performance verification are presented in Chapter 4. Results of the optimization process and experimental efforts are presented in Chapters 5 and 6, respectively. Conclusions and recommendations for future work are given in Chapter 7.

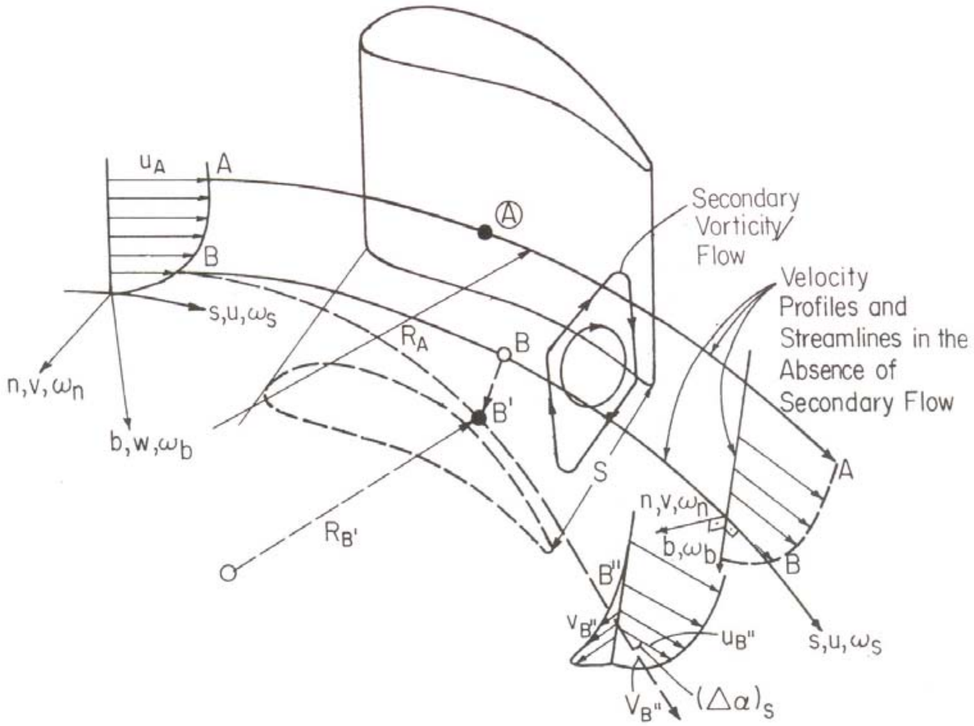

Figure 1.1 Inviscid theory of secondary flow development (Lakshminarayana, 1996).

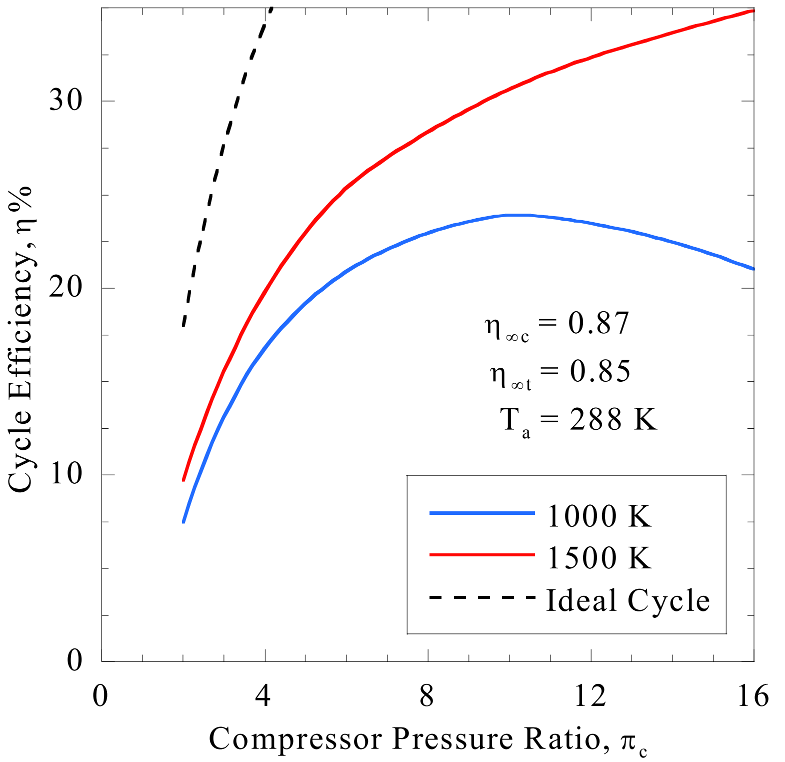

Figure 1.2 Cycle efficiency is a function of pressure ratio and turbine inlet temperature (adapted from Cohen, Rogers, and Saravanamuttoo, 1987).

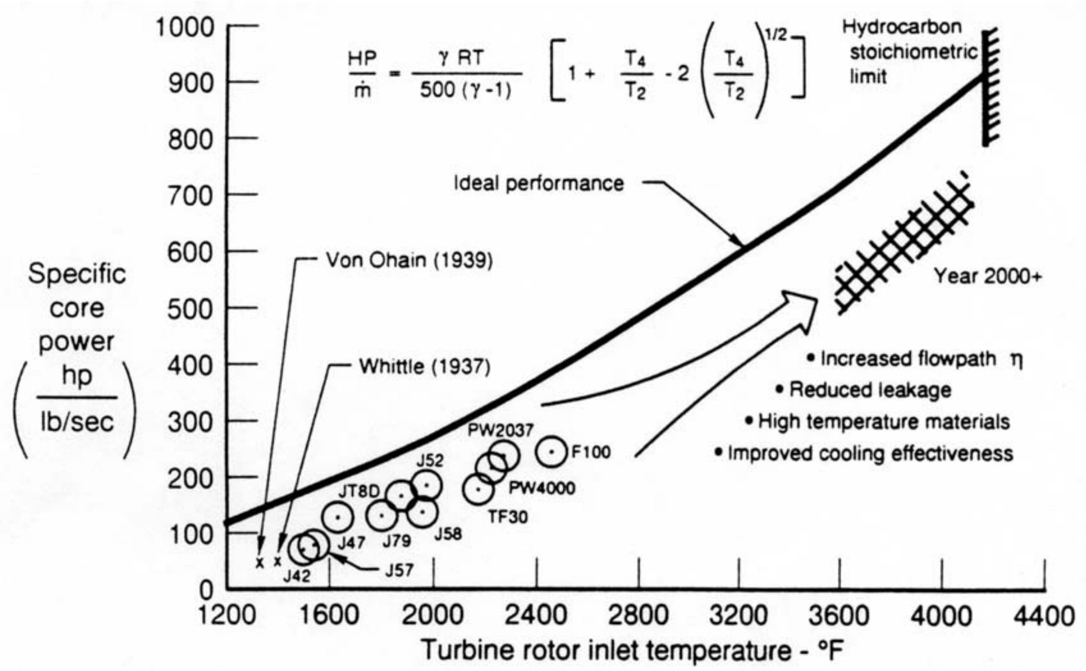

Figure 1.3 Specific core power as a function of turbine rotor inlet temperature as presented by Koff, 1991.

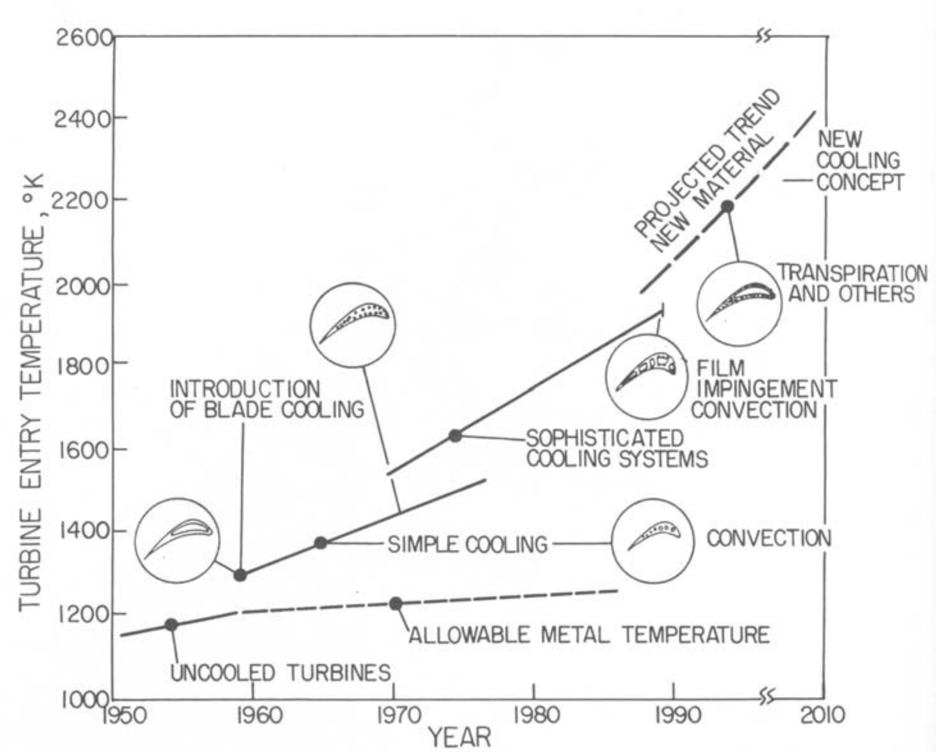

Figure 1.4 Historical and projected future trends in turbine cooling technology (Clifford, 1985).