RECENT DEVELOPMENTS IN TURBINE BLADE INTERNAL COOLING

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ABSTRACT

Gas turbines are used extensively for aircraft propulsion, land-based power generation, and industrial applications. Thermal efficiency and power output of gas turbines increase with increasing turbine rotor inlet temperature (RIT). The current RIT level in advanced gas turbines is far above the melting point of the blade material. Therefore, along with high temperature material development, a sophisticated cooling scheme must be developed for continuous safe operation of gas turbines with high performance. Gas turbine blades are cooled internally and externally; this paper focuses on turbine blade internal cooling. Internal cooling is achieved by passing the coolant through several rib-enhanced serpentine passages inside the blade and extracting the heat from the outside of the blades. Both jet impingement and pin-fin-cooling are also used as a method of internal cooling. In the past number of years there has been considerable progress in turbine blade internal cooling research and this paper is limited to reviewing a few selected publications to reflect recent developments in turbine blade internal cooling.

Introduction

Advanced gas turbine engines operate at high temperatures (1200-1400°C) to improve thermal efficiency and power output. As the turbine inlet temperature increases, the heat transferred to the turbine blades also increases. The level and variation in the temperature within the blade material (which causes thermal stresses) must be limited to achieve reasonable durability goals. The operating temperatures are far above the permissible metal temperatures. Therefore, there is a need to cool the blades for safe operation. The blades are cooled by extracted air from the compressor of the engine. Since this extraction incurs a penalty to the thermal efficiency, it is necessary to understand and optimize the cooling technique, operating conditions, and turbine blade configuration.

Figure 1 shows the common cooling technique with three major internal cooling zones in a turbine blade. The leading edge is cooled by jet impingement, the trailing edge is cooled by pin-fins, and the middle portion is cooled by serpentine rib-roughened coolant passages. This paper is limited to reviewing a few selected publications that dealt with the common cooling techniques. The compound and new suggested cooling techniques are only briefly mentioned. In particular, this paper focuses on the effect of rotation on the rotor coolant passages heat transfer.

Rib turbulated cooling

In advanced gas turbine blades, repeated rib turbulence promoters are cast on two opposite walls of internal cooling passages to enhance heat transfer. Thermal energy conducts from the external pressure and suction surfaces of turbine blades to the inner zones and that heat is extracted by internal cooling.

The internal cooling passages are mostly modeled as short rectangular or square channels with different aspect ratios. The heat transfer performance in a stationary ribbed channel primarily depends on the channel aspect ratio, the rib configuration, and the flow Reynolds number. There have been many fundamental studies to understand the heat transfer enhancement phenomena by the flow separation caused by ribs. In general, ribs used for experimental studies are square in cross-section with a typical relative rib height of 10% of channel hydraulic diameter, and a rib spacing-to-height ratio varying from 5 to 15. However, today's airfoils have more complicated rib shapes and angles, and smaller gas turbines have high blockage ribs at closer spacing.

Jet impingement cooling

Among all heat transfer enhancement techniques, jet impingement has the most significant potential to increase the local heat transfer coefficient. Jet impingement heat transfer is most suitable for the leading edge of an airfoil, where the thermal load is highest and a thicker cross-section of this portion of the airfoil can suitably accommodate impingement cooling. There are several arrangements possible with cooling jets and different aspects need to be considered before optimizing an efficient heat transfer design. There are some studies focused on the effects of jet-hole size and distribution, cooling channel cross-section, and the target surface shape on the heat transfer coefficient distribution. However, most impingement cooling studies are for non-rotating blades, only a few studies focus on rotor blade impingement cooling.

Pin-fin-cooling

Pins are mostly used in the narrow trailing edge of an airfoil where impingement and ribbed channels cannot be accommodated due to manufacturing constraint. Pin-fins commonly used in turbine cooling have pin height-to-diameter ratio between ½ and 4. Heat transfer in turbine pin-fin array combines the cylinder heat transfer and endwall heat transfer. Due to the turbulence enhancement caused by pins, heat transfer from endwalls is higher than smooth wall conditions; however, mounting pins may cover a considerable surface area, and that area needs to be compensated for by the pin surface area. There have been many studies that evaluated the effects of pin size, distribution, shape, and pin-fin-cooling with extration on the heat transfer coefficient distribution. However, all pin-fin-cooling studies so far are for non-rotating blades, none for rotor blade pin-fin-cooling.

Compound and new cooling techniques

Several internal heat transfer enhancement techniques are discussed in previous sections. Most common methods of heat transfer augmentation in gas-turbine airfoils are ribs, pins, jet impingement, and flow disturbing inserts. It is shown that these enhancement techniques increase heat transfer coefficients, but can combining these techniques increase the heat transfer coefficient more? Several researchers have combined these heat transfer enhancement techniques to improve the heat transfer coefficient. However, it is not always recommended to combine more than one heat transfer augmentation technique. Besides compounding more than one heat transfer enhancement technique, there are attempts to incorporate new concepts, e.g., jet swirlers, dimpled surfaces, heat pipes, in the turbo-machinery cooling. Several studies are available on new cooling techniques, application, and introductory concepts in that regard are also reviewed.

Rotational effect on cooling

Heat transfer in rotating coolant passages is very different from that in stationary coolant passages. Both Coriolis and rotating buoyancy forces can alter the flow and temperature profiles in the rotor coolant passages and affect their surface heat transfer coefficient distributions. It is very important to determine the local heat transfer distributions in the rotor coolant passages with impingement cooling, rib turbulated cooling, or pinned cooling under typical engine cooling flow, coolant-to-blade temperature difference (buoyancy effect), and rotating conditions. Effects of coolant passage cross-section and orientation on rotating heat transfer are also important and are included in this paper. It is also important to determine the associated coolant passage pressure losses information for a given internal cooling design. This can help in designing an efficient cooling system and prevent local hotspot overheating of the rotor blade.

Concluding Remarks

For a typical cooling arrangement in a modern rotor blade, impingement cooling is used in the leading edge and pin-fin-cooling is used in the narrow trailing edge, and mid-section is cooled by rib-turbulated convection. In this paper, mid-section rib turbulated convection cooling is discussed in detail. However, majority works are for the square ribbed channels without bleed holes. More studies are needed for rectangular ribbed passages with and without film holes under realistic coolant flow, thermal, and rotation conditions. Also, more studies are needed for rotating impingement cooling as well as rotating pin-fin-cooling in order to guide the efficient rotor blade internal cooling designs.

Fig. 1. The schematic of a modern gas turbine blade with common cooling techniques.