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Evolution of Rolls-Royce air-cooled turbine blades and feature analysis

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Abstract

During past few decades there has been significant increase in turbine entry temperature (TET) in order to improve gas turbine ability and efficiency, which represents a huge challenge to turbine blades. Rolls-Royce maintains world-leading technology and capability in gas turbines design and manufacture, this study mainly focuses on the evolution of air-cooled turbine blades fabricated by Rolls-Royce, which shows that turbine blade developments are increasingly dependent on the improvement of material science and blade cooling technology. Moreover, its unique blade tip designs which minimize over-tip leakage are also reviewed. Future developments to improve turbine blade ability and reliability including high temperature materials, blade cooling technology and CFD analyzing approach are discussed.

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Keywords: air-cooled turbine blade; turbine entry temperature; over-tip leakage; blade cooling

1. Introduction

Since the jet engine was firstly invented during the World War II, the demand for gas turbines with better performance as the power plant for aircraft keeps increasing.

In a gas turbine, the combustor exit gas with extremely high temperature and pressure flows through the turbine cascades. Turbine blades extract energy from the hot gas and drive the compressor. Theoretically, the improvement of thrust and efficiency of today's gas turbine engines depends primarily on continuously increasing turbine entry

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temperature (TET), and there has been a very significant increase in TET in order to improve gas turbine performance since gas turbines were invented. For the early gas turbines with uncooled turbine blades installed, TET was limited to about 1050 centigrade due to the blade material properties. Since blade cooling was first introduced on the Conway engine, Rolls-Royce has been focusing on improving cooled turbine blade design so as to minimize bleed air and maximize overall efficiency. Currently improved material properties and advanced blade cooling technologies have been developed to ensure that turbine blades could withstand such high temperature.

As one of the largest gas turbine manufacturers in the world, Rolls-Royce has successfully developed a series of different types of engines (turbofan, turbo-prop, turbo-jet and turbo-shaft, etc.) with various power ratings and applications. Their products serve civil airlines, military aircrafts and energy industries for the worldwide costumers as well. Rolls-Royce maintains the world most advanced technologies and capability in turbine blade design with its unique features. According to these facts, this paper reviews the development of Rolls-Royce's gas turbine engines, in particular the Conway, RB211 and Trent engines. Moreover, the evolution of Rolls-Royce air-cooled turbine blades and design features of the turbine blades are highlighted. The lessons learned from Rolls-Royce can help to understand the mechanism of blade cooling and the design philosophy on turbine blades. It could also inspire people to develop and optimize air-cooled turbine blade design in China.

2. History of Rolls-Royce jet engine

Although the concept of the jet engine was first patented by Frank Whittle in 1930, it wasn't successfully introduced until 1941 when the Whittle engine accomplished the first flight-test, since then it became the basis of modern jet engines. In a jet engine, air is taken into compressor, after that, compressed air mixes with fuel and burns in the combustor chamber, and then hot gas flows through a turbine, a turbine can extract energy from the combusted hot gas and drives the compressor, gas is further accelerated in a nozzle and generates thrust for the aircraft.

In 1943, Rolls-Royce moved into this new area in gas turbine industry by taking over the task of Whittle W2B modification. The new version Whittle W2B engine was named Rolls-Royce Well and with a thrust around 7kN. Based on Whittle engine, some new gas turbines (Nene engine and its scaled version, Derwent, etc.) were developed to power different aircrafts during 1940s. Dart engine and Avon engine are also very successful products among early Roll-Royce engines in both military and civil market. [1,2]

The invention of "By-pass engine" is a remarkable event in gas turbine history. [2] A twin-spool turbofan engine Rolls-Royce Conway with a by-pass ratio of 0.42 was firstly put into service in 1962. Compared with a turbo-jet engine, a turbofan engine could provide higher thrust with higher efficiency and reduced noise. Meanwhile, the concept of blade cooling started to be applied in turbine design of Conway engine, which enables turbine blades to operate in a much higher TET than their melting point resulting in a large increase in gas turbine thrust and efficiency.

In the 1960s, JT9 high by-pass ratio turbofan engine developed by Pratt & Whitney made great success in international transport market. Compared with the first generation turbofan engines, it operates in high by-pass ratio, high pressure ratio and high TET, resulting in a significant increase in thrust and a decrease in SFC. In this context, Rolls-Royce began to design a competitive tri-spool high by-pass ratio engine RB211 in late 1960s. Relative to twin-spool engines, a tri-spool engine enable HP, IP and LP rotors to operate at optimal rotational speed, resulting in lower TET, besides that, it is also stiffer and lighter due to reduced shaft length. In developing RB211, Rolls-Royce experienced great challenges in both technology and finance due to the complexity of tri-spool configuration, led to a bankruptcy and nationalization between 1971 and 1978. The first RB211 engine ran in 1968, and then completed the first flight test in 1970. 27 months after it first ran, RB211 engine achieved Certification and Entry into Service in 1972. After solving enormous technical problems in performance and reliability, RB211 has been proved to be a successful engine. Based on RB211-22B, the initially certificated variant, Rolls-Royce carried out an extensive modification program to enhance the performance and to cover different thrust ratings. Generally these variants and upgrades are classified into two groups: RB211-524 series and RB211-535 series.

The Trent is a prolific family of 3-spool, high by-pass ratio turbofan engines developed from the RB211 with thrust ratings between 53,000 to 95,000 lbs-force (240 to 420 kN). In 1988, the original Trent 600, formerly named RB211-524L, was designed as a variation of RB211-524G/H with increased thrust rating intended to power the MD-

11. Although the engine's development was stopped due to the cancellation of MD-11 program, Trent 600 is the basis of Trent family engines.[3] Moreover, each variant of the Trent has incorporated new technology made available by the technology programs that have run in parallel with and ahead of the next engine launch, and validated new technologies are also applied to upgrade earlier RB211 and Trent engines, which keeps Rolls-Royce engines powerful and competitive.

3. Evolution of Rolls-Royce air-cooled turbine blades

3.1. Requirements for the turbine blades

Nowadays, advanced Trent engine could provide about 60 times thrust relative to early Whittle W2, meanwhile, the thrust to weight ratio triples and SFC cuts in half. The same as other competitors, the improvement of thrust and efficiency of gas turbine engines highly depends on continuously increased TET.

As it is shown in Fig.1, during past 70 years, TET increased from 1050K for Whittle engine to higher than 1800K for Trent 900. At the same time, superalloys used for turbine blades have been improved in steps to upgrade temperature capability, were firstly wrought, and followed by equi-axed cast alloys, directionally-solidified (DS) and single-crystal (SC) alloys. However, the progress in materials is relatively slow. Currently, TET is about 350K higher than turbine blade materials melting points, as a result, blade cooling technology have to play a key role to bridge this big gap to ensure turbine blade operational safety. Blade cooling was first brought into gas turbine in Conway in 1962, since then, blade cooling has played a critical role in gas turbine. Cooling air is extracted from compressor and pumped to turbine nozzle guide vanes and blades, coolant flows through the blade cavities and takes away part of heat transferred from hot gas to blade surface, and a little coolant is ejected from discrete film holes and trailing edge slots to generate very thin films, which insulates turbine blade surface from hot mainstream gas to protect turbine blades.

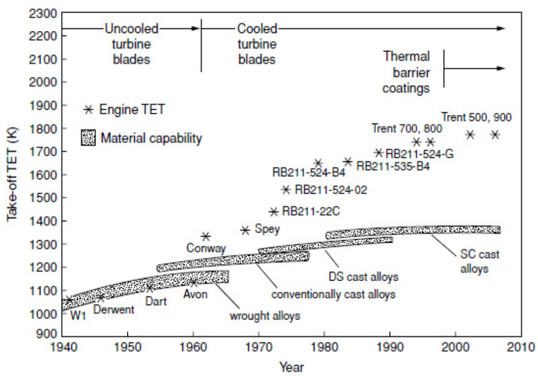

Fig.1. Development in TET of Rolls-Royce engines [4]

Turbine blades are subjected to the most severe operation condition due to very high temperature, high turbulent flow and high rotational speed, which possibly leads to a number of failure modes such as: low cycle fatigue, high cycle fatigue, thermal fatigue, creep damage, environmental attack (oxidation, sulphidation, hot corrosion), and combined failure mechanism (oxidation/erosion). [5]

As a result, turbine blade materials must have high melting points, good oxidation/corrosion resistance and high temperature strength. Despite massive progress on material technology has been achieved to provide higher temperature capability and performance, turbine blades are still required to be properly cooled, so as to ensure metal temperature and temperature gradient match the maximum thermal stress, and minimize coolant flow to reduce aerodynamic losses caused by blade cooling.[6]

3.2. Early Rolls-Royce turbine blades

In the 1960s, air-cooled turbine blade was first applied in Rolls-Royce Conway design to replace solid blade. As a big leap, it made history by introducing blade cooling into gas turbine industry. Since then, turbine entry temperature has not been limited by the metal melting point.

Fig. 2 shows typical Rolls-Royce cooled turbine blades (from Conway and Spey, respectively) early in the 1960s. Simple convection cooling was applied to cool the blades. For the Conway blade, Nickel based wrought alloy Nimonic 105 was adopted to forge the blade which had three straight internal passages. Cooling air was fed from 2 inlets at the shank of the root and flowed radially through two single passages from root to tip, then combined and flowed through the middle passage, finally discharged from the outlet placed at the shank region in the suction side. In this procedure, heat absorbed by the blade surface from the mainstream gas was removed by the coolant. 1.4% cooling air was bled from the compressor to achieve a mid-span temperature drop of 120K. As a result, blade life increased significantly to more than 10,000 hours compared to 75 hours without cooling. The cooling configuration for Spey is the same except that cooling passage is increased and coolant discharges from tip. [7, 8]

Although convection cooling effectively reduced blade surface temperature, forged blade has limitations: its high temperature strength is relatively weak and it is difficult to form complex internal cooling passages.

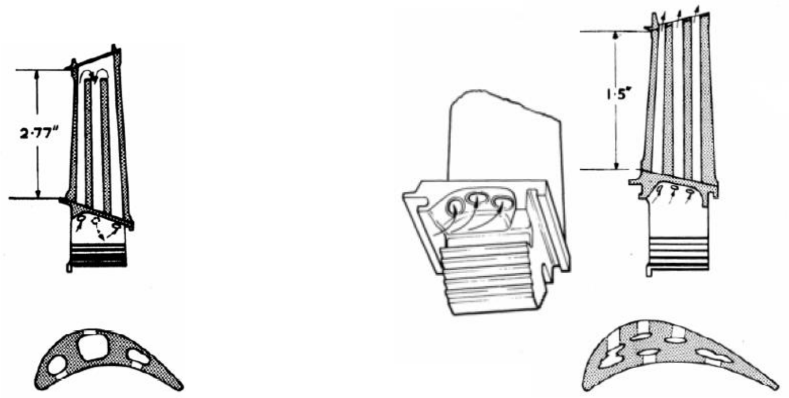

Fig.2. Rolls-Royce Conway turbine blade (left) and Rolls-Royce Spey turbine blade (right)

3.3. Rolls-Royce engine turbine blade from RB211 to Trent

The RB211-22B engine entered service in 1972 in the Lockheed Tri-Star aircraft, the single stage high pressure turbine blade was designed as an air-cooled blade. The main structure of -22B turbine blade inherited from the design of Conway and Spey. The blade has an interlocked shroud and a fir-tree root, coolant is also fed from the shank and flows through internal radial passages to cool the airfoil. Besides that, both low pressure and high pressure air is delivered as coolant. Discrete film holes are designed to enhance cooling in the leading edge, trailing edge and suction side of the airfoil, so as to satisfy increased TET (1550K).

But from entry into service, combined effect of high gas temperature and high shaft speed resulted in thermal fatigue and creep in a relatively short time, and reliability of the blade was proved to be a big problem. Therefore modifications must be carried out to improve reliability and blade life. As shown in Fig.3, it is a long term evolution in both better materials and better cooling technology for the RB211 turbine blades.

By 1977, investment casting had been developed to design a new turbine blade in RB211-524 engine. The cooling configuration was similar to the -22B, but the root and the HPT disc were redesigned to enable coolant to feed from both the root and the shank. Moreover, full HP air and extensive film cooling produced more effective cooling, and equi-axed casting improved mechanical properties and temperature level of the blade. TET increased to 1660K, more than 100K higher than -22B.

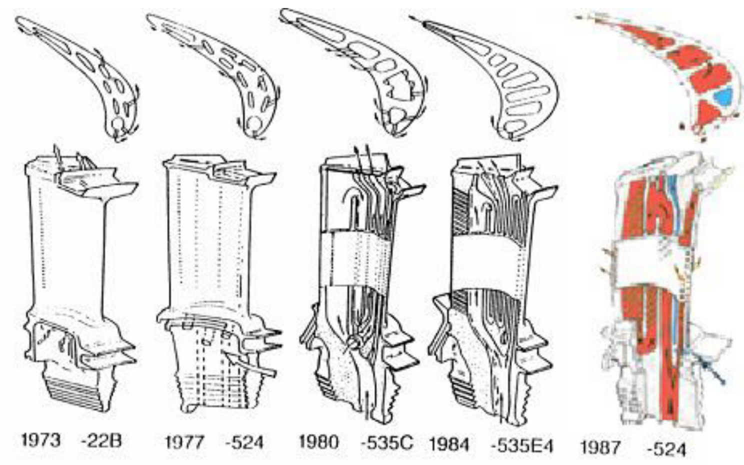

Fig.3. Development of design for RB211 turbine blade [8, 9]

A completely new design of HP turbine blade was accomplished and applied in RB211-535C, a new variant of -22B. As the TET kept the same as -524, evolutional cooling configuration and first generation directionally-solidified (DS) cast alloy were developed to achieve the desired service reliability. The profile of the blade was redesigned to enable larger cooling cavities, serpentine multi passes. Besides, horizontal ribs were set to increase area and intensity of internal heat exchange, which are still widely used in modern turbine blades. HP air was introduced to cool the blade from the root, another sole airflow pumped into the midspan channel of the blade.

In 1984, Rolls-Royce updated -535C to -535E4. In the HP turbine blade design, serpentine multi passes were modified and the second generation DS alloy was applied to cast the blade, which increased TET to 1680K and consequently provided an 8 percent reduction in overall fuel consumption relative to -535C.

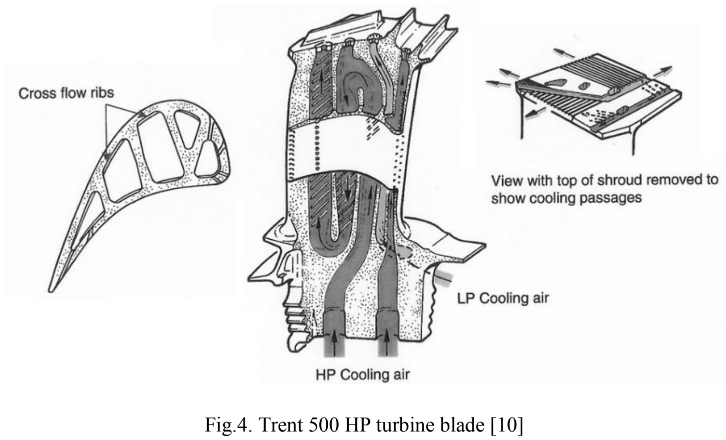

Fig.4. Trent 500 HP turbine blade [10]

The turbine blade has been further developed on the RB211-535D, the RB211-524G/H and subsequently the Trent engine family. The cooling configurations are similar. As illustrated in Fig.4, Trent 500 inherited multi-passes serpentine design and film cooling to cool the airfoil. Optimized cross flow rigs in the passages enhance heat transfer without excessive pressure drop. Besides the HP cooling circuit, another LP air flow path is set to cool the leading edge and discharges from the blade tip. Since the TET exceeds 1850K, the blade shroud is also cooled by parallel cooling passages. Sophisticated 3D shaped film holes on the leading edge and trailing edge further improved cooling effect by encouraging jet lateral expansion and limiting lift-off. [11,12] Temperature capacity is further improved by applying single crystal (CMSX-4) casting and thermal barrier coating.

Soluble core [13] manufacturing technology was developed to cast single crystal Trent 1000 HPT blade. In this procedure, about 20% weight salt blended with ceramic material to form a homogeneous mixture and then the mixture was compacted to high density soluble core which could withstand higher die casting temperatures than conventional salt cores. After casting, the soluble core was removed by high pressure steam or hot water and the salt and ceramic materials could be reused. It shows obvious advantages in casting turbine blades especially with complicated internal cooling passages.

3.4. Unique design features

During past 70 years, Rolls-Royce has developed leading technologies in turbine blade design. Unique experience obtained in a long history makes the design philosophy differ from other competitors.

- Temperature margin

On RB211 and Trent engines, pre-swirl nozzles are applied to swirl the cooling air in the direction of rotation of the disc. Air expands in the channels to decrease temperature, and then it flows into the cooling passage with a high velocity. As a result, the coolant inlet temperature can be 40~60K lower relative to that without pre-swirl. This technology is also applied by other gas turbine manufactures. Due to the tri-spool configuration of RB211 and Trent engines, HP rotor operates at a much higher shaft speed compared with twin-spool configuration (JT9D and CF6, etc.), at the same overall pressure ratio and TET, the relative total temperature which turbine blade really experiences can be 27~55K lower. [3] So the turbine blades have a large temperature margin.

- Coolant feeding

Although multi-passes is widely applied in current advanced turbine blade cooling, the main difference between Rolls-Royce and other gas turbine providers is the way of coolant feeding. Traditionally, Rolls-Royce prefers to apply both HP air and LP air to cool the same blade, which is seldom adopted by the other companies. The HP air is used as main cooling circuit and provides film cooling for the leading edge and pressure side, while LP air is used to cool the leading edge in convection cooling and discharged from the tip. This cooling arrangement increases complexity of both secondary air system and cooling configuration of the blade, and the risk of thermal stress caused by the temperature difference between the HP air and LP air, but the designers have well balanced the profits and the penalties.

- Blade tip design

In a gas turbine, the gap between rotational blade tip and stationary casing and pressure difference between both sides of the blade dramatically result in over tip leakage (OTL) and leakage vortex. This phenomenon significantly weakens turbine performance. As a result, active clearance control is an option to minimize the losses, but for Rolls-Royce, this technology has not been developed until Trent 500 in 1997, alternatively Rolls-Royce chose to optimize shrouded and unshrouded blade tip design for different applications.

Except for Rolls-Royce, there is seldom application of shrouded tip design on HPT blade. The main advantages of blade shroud are that it could reduce over-tip loss and improve fatigue strength. On the other hand, it needs more cooling flow, besides, the centrifugal stresses of the blade and disk increases and manufacture cost also increases. Actually, Rolls-Royce has unique experience in developing both shrouded (RB211 and Trent, etc.) and unshrouded (EJ200, EFE, etc.) turbine blades, and the choice mainly depends on the specific application.

RB211 and Trent engines have similar shrouded tip design (see Fig. 5) with two fences and two fins. Fins on the blade tip which match with the honeycomb on the stationary casing enable turbine rotor to have a relatively small clearance to control the over-tip losses. Moreover, convergent channels are formed between every two fences, and discharged cooling air and over-tip flow accelerate in the channels, so the fences are used for energy reclamation. Consequently, the shrouded blade tip with 2 fins and 2 fences could result in much lower stage efficiency loss compared to unshrouded tip (see Fig. 6).

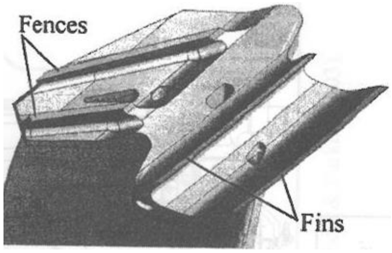

Fig.5. Shrouded RB211 turbine blade

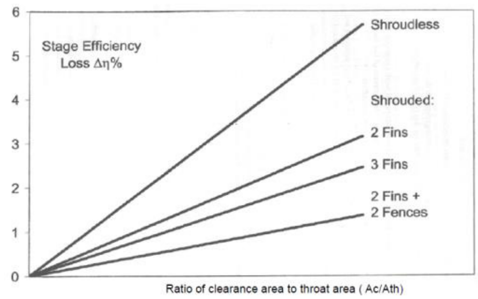

Fig.6. Comparison of OTL loss exchange rates for shrouded and unshrouded HP Turbines [15]

For the military engines, Rolls-Royce patented a tip sealing configuration for unshrouded turbine blades [16], which is different from conventional flat tip or squealer tip, has been actually used in EJ200 HPT blade design (See Fig.7) to minimize over tip leakage. According to the patent, a gutter is placed on the blade tip which is wider than aerofoil adjacent to the trailing edge of the blade, and at least a part of the gutter is offset towards the pressure side. In operation, the leakage flow across the tip is trapped within the gutter. A vortex is generated and guided to flow along the gutter and exhausts from the trailing edge. The area of the gutter is sufficient to enable the tip leakage to flow through it and avoids the leakage flow crossing over the suction side of the blade and flowing into the mainstream.

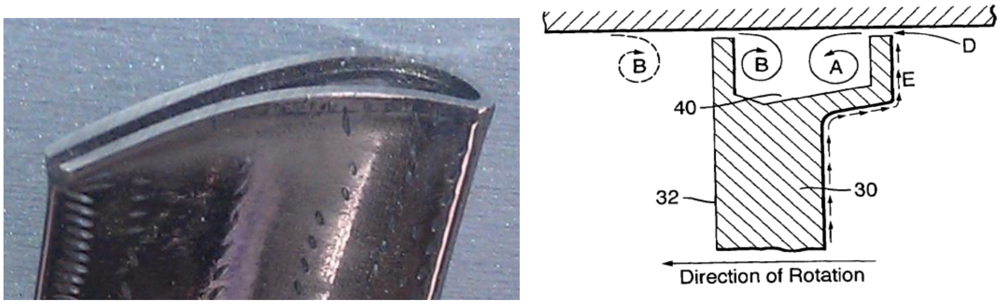

Fig.7. EJ200 blade tip (left) and over tip flow mechanism (right)

4. Future directions

Currently, Rolls-Royce is working under many technology programs (ACARE, EEFAE-ANTLE/CLEAN, VITAL, E3E, EFE, etc.) to demonstrate the future gas turbine technologies, aiming to improve gas turbine performance and affordability and reduce emission and noise. A key issue that must be considered in these programs is to design cooled HPT blade with high temperature capacity, high reliability and low losses.

4.1. Material technology

In 1960s, investment casting was developed to manufacture turbine blades instead of forging. It is a big step to improve blade capacity by improving blade materials and manufacturing. Since then, directionally-solidified (DS), single-crystal (SC) cast alloys and casting processes have been developed to adapt increased turbine temperature. Especially, single crystal eliminates grain boundaries so as to improve the mechanical properties and temperature capacity of turbine blades. Currently, the western countries have been developed three generations of single crystal materials. Rene N6 and CSMX-10 are typical the third generation single crystal materials which contain about 6% Re, compared with the second generation SC. Their working temperatures increase about 30K. Creep strength and oxidation/hot corrosion resistance are also improved. Single crystal casting has been considered as the key technology in Rolls-Royce future strategy and Rolls-Royce has patented a lot of applications on it. [17~20]

As far as materials are concerned, ceramic-matrix composites (CMCs) which comprise a ceramic matrix reinforced by a refractory fibre, such as silicon carbide (SiC) fibre, offer low density, high hardness and superior thermal and chemical resistance, hence the CMCs attract enough attention to be investigated for the potential application on gas turbine hot section components to replace conventional superalloys. The main benefit of CMCs could offer is to increase overall efficiency because of higher TET, less coolant mass flow and lower weight. Rolls-Royce Allison has tested and demonstrated ceramic NGVs for 815 hours on Model 501-K turbine, and results show that long term oxidation is a big challenge for stationary CMCs components. Environmental barrier coatings (EBC) used to protect CMCs will be tested in next phase.[21~22] However, CMCs would not be applied to produce air-cooled turbine blades until they overcomes significant challenges in complex airfoils fabricating, high stress region design and high temperature oxidation/corrosion.

Besides that, thermal barrier coating (TBC) is another economical and effective way to protect turbine blades. With TBCs, at constant coolant flow, life of the blade can be increased due to reduced blade temperature. On the other hand, at the same blade temperature, TBCs enable gas temperature to increases by about 65°C, which definitely improves gas turbine efficiency and reduces SFC.[23] Currently, advanced TBCs could result in about 150K temperature drop on turbine blades. According to estimation, British Airline could save 25 million Pound per year on fuel costs due to application of advanced TBCs in Trent engines.[24] In the future, TBCs will the further developed to achieve higher temperature resistance, higher environment resistance and higher reliability and durability.

4.2. Advanced cooling technology

Cooling technology development plays a vital part in technology upgrade of Rolls-Royce. Generally there are two ways to develop high effectiveness cooling schemes: to optimize current cooling configurations and coolant flow paths and study new film cooling geometries and arrangements; to develop novel cooling scheme such as transpiration cooling and dual-wall cooling.

Transpiration cooling offers very high cooling effectiveness by ejecting cooling air through a porous wall. A well uniformed film is generated consequently to insulate blade surface from mainstream hot gases, but inevitable blockage of the porous wall is a great challenge which could seriously reduce cooling effectiveness and damage the blade.

Dual-wall cooling is a group of advanced cooling schemes originated from Rolls-Royce “Transply cooling”, a highly effective semi-transpiration cooling scheme, which was firstly applied in Rolls-Royce Tay to cool the wall of combustor chamber. Since then, great efforts have been made to copy this novel cooling scheme to turbine blade cooling. Many similar cooling schemes have been developed and demonstrated as “Transply”, “Castcool”, “Lamilloy”, “Supercool” and “Dual-wall cooling” in Europe and the US. Generally, an outer wall and an inner wall are cast to form the wall of the aerofoil. Air is forced into hollowed layer between the outer wall and inner wall through tiny passages, heat transfer between the coolant and the wall is enhanced by impingement jets, pedestals and ribs and film cooling rows. Rolls-Royce has patented a dual-wall cooling scheme and produced turbine blades with dual-wall cooling in CMSX-4 single crystal [25~27]. Rolls-Royce considers dual-wall cooling as a key technology to realize efficient cooling and reduce emissions. Rolls-Royce plans further to apply dual-wall cooling blade in FAA Continuous Lower Energy, Emissions& Noise (CLEEN) program to reduce cooling flow and improve overall efficiency. Related casting/manufacturing technologies for dual-wall cooling blade will be developed and validated. [28]

4.3. Winglet blade tip design

Rolls-Royce has investigated a novel tip sealing configuration named “Winglet” under the ANTLE program (Advanced near Term Low Emissions). [29~30] Two small aerofoils overhang both the pressure side and the suction side at the blade tip, forming a passage from the leading edge to the trailing edge. The winglet configuration (see Fig.8) has been applied to a turbine blade and rig tested at Trent 500 operating point. Experimental and numerical results show that winglet tip exhibits comparative over tip leakage reduction compared to shrouded tip with two fins, which is about 45% lower than unshrouded blade tip.

However, Rolls-Royce and Cambridge University continue to investigate and optimize the winglet tip configurations. Modification of the shapes of winglet and introducing of coolant jet are applied to improve the technology readiness level in the future. [31~34]

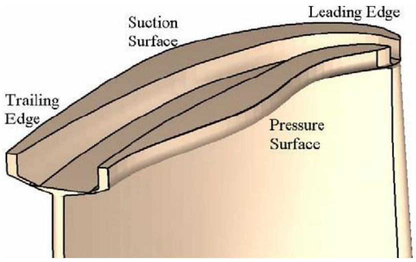

Fig. 8 Geometry of winglet tip concept [29]

4.4. Turbine blade flow and heat transfer analysis

Gas turbine blades operate in high temperature, high pressure and high rotation speed, and are cooled by air flowing through internal passages. The flow field both in the mainstream and internal passages and heat transfer between the flow and walls are very complicated. All these boundary conditions are necessary to accurately predict blade temperature but could hardly be measured. Alternatively Rolls-Royce applied CFD to simulate the flow filed and wall heat transfer coefficients, and consequently to plot blade temperature distributions in FEA. The accuracy of CFD results is validated through in-engine measurement results. Besides, conjugated CFD methods have been developed to solve both the internal flow and mainstream and the blade at the same time, which could be used to optimize current cooling design and develop new cooling schemes. [19]

5. Conclusions

Typical air-cooled turbine blades produced by Rolls-Royce are reviewed, the evolution of the blades and advanced technologies which could be applied in the future are summarized as follows:

(1) Over a long term, the gas turbine TET keeps increasing. Turbine blades are highly dependent on development in material science and blade cooling technology.

(2) Blade materials have been developed from wrought alloys to investment casting alloys (Equi-axed, DS, SC), allowing higher temperature capability and environmental attack resistance. Thermal barrier coating as an economical and effective way to protect turbine blade attracts more attention than ever. Moreover, CMCs are considered as future blade material, although many challenges need to be overcome.

(3) Blade cooling technology has been developed from single pass convection cooling to sophisticated multi-pass serpentine cooling coupled with film cooling. Advanced cooling schemes such as dual-wall cooling will be the future direction.

(4) Blade tip design which is used to minimize over-tip leakage and improve turbine efficiency needs to be further developed.

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