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Investigation into the Effects of Operating Conditions and Design Parameters on the Creep Life of High Pressure Turbine Blades in a Stationary Gas Turbine Engine

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A physics–based model is used to investigate the relationship between operating conditions and design parameters on the creep life of a stationary gas turbine high pressure turbine (HPT) blade. A performance model is used to size the blade and to determine its stresses. The effects of radial temperature distortion, turbine inlet temperature, ambient temperature and compressor degradation on creep life are then examined. The results show variations in creep life and failure location along the span of the blade enabling better informed design and maintenance decisions.

Keywords: Lifing, creep, turbine, blade, performance, degradation

1. Introduction

Gas turbines are required to operate under conditions of high temperature and mechanical loading. At these conditions, the components undergo various time–dependent degradations that result in failure mechanisms such as low/high cycle fatigue, corrosion/oxidation and creep [10]. Creep significantly reduces the component life of stationary gas turbines. The creep life consumption of a gas turbine depends on the design of the hot section components, duty cycle and the environment in which it operates. The design parameters of the hot section components are determined by both aerodynamic and structural characteristics. Owing to the possible interaction between these parameters and the intended operating conditions, it is necessary to consider the effect of creep on the life of the hot section components at the design stage. A better understanding of the failure mechanisms will help designers in the trade–off between different design options and will also help operators to make informed maintenance decisions.

Although several researchers have stressed the effect of material and engine performance on turbine blade creep life, limited information is available in the literature on the effect of design parameters and operating conditions. Furthermore, creep lifing approaches that are available often require the integration of complex analyses and a multi–disciplinary approach [6].

In this work the impact of operating conditions and design parameters on creep life are investigated. Using a thermodynamic performance model combined with a physics–based model, mechanical and thermal stress analyses are performed on the High Pressure Turbine (HPT) first stage rotor blade of a stationary gas turbine engine. The Larson Miller Parameter (LMP) method is then used to estimate the remaining creep life of the blade. The aim is to build a relationship between creep life consumption at off–design operating conditions and parameters such as blade radial temperature profile (represented by a radial temperature distribution factor (RTDF)), ambient temperature (T_{amb}) and turbine entry temperature (TET). The effect of compressor fouling on creep life is also examined.

2. Performance simulation and blade geometry

Based on the engine configuration shown in Fig. 1, a performance model was created using "Turbomatch" which is an existing component based engine performance tool developed at Cranfield University. This software was used to develop and run representative thermodynamic models of the engine investigated. Turbomatch has the ability to perform steady state engine performance calculations at both design point and off design conditions. Tab. 1 lists the engine performance parameters.

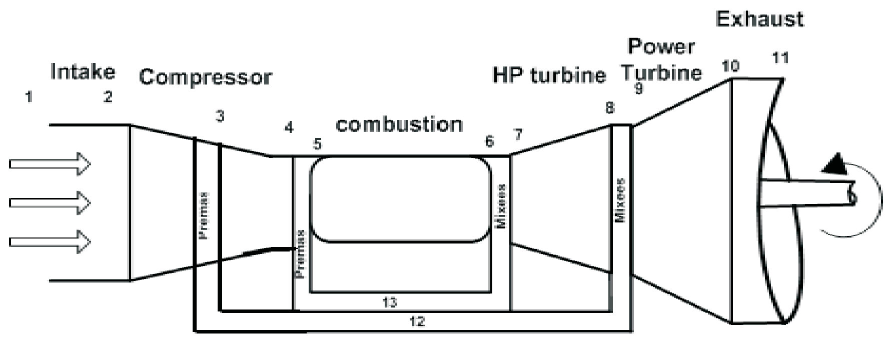

Figure 1 General layout of the engine

The first stage of the high pressure turbine blade was sized using the constant nozzle method [2], [8], [9]. Although the turbine is a two–stage turbine, only the first stage blade was considered during the design process. The initial data used in the design process was based on a literature survey. The blade geometry specifications at the mid–height are presented in Tab. 2.

Table 1 Engine performance parameters

Parameter	Value
Pressure ratio	23.1
Power output	30.2 kW(40.5 shp)
Exhaust gas flow rate	82.5 Kg/s
Thermal efficiency	28-40%

Table 2 Blade geometry specification at the mean height

Geometrical Parameter at Mean Height	Values	Unit
Leding Edge/Trailing Edge radius	0.3889	m
Inlet annulus area	0.1038	m^2
Blade chord	2.909	cm
Height to chord ratio	1.46	

3. Blade creep life assessment

In this study, a creep life model was developed and applied to the high pressure turbine first stage rotor blade of a typical stationary gas turbine. Fig. 2 shows the methodology used for the blade creep life assessment. The model consists of the sub–models: performance, sizing, stress, thermal and creep. The output of the "Turbomatch" engine model was used as input to the blade design process and was combined with the blade geometry data to obtain the blade stress distribution. The blade metal temperature along the span of the blade was also obtained from the estimated radial gas temperature distribution. The output of the stress/thermal model was used as input in the creep model (LMP) to estimate the blade's remaining creep life. The properties of the Nimonic alloy used in the investigation are: density 8180 Kg/m^3, melting temperature 1310^{o}C and specific heat capacity 753 J/Kg^{o}C [7].

3.1. *Stress model*

The details of the blade stress model are presented in [2]. The output of the stress model is the maximum stress at the blade section when stresses due to both centrifugal loading and gas bending moment are added. It is important to note that the location where the maximum stress occurs (either at the leading edge, trailing edge or the blade back) largely depends on the operating condition and the geometry of the blade.

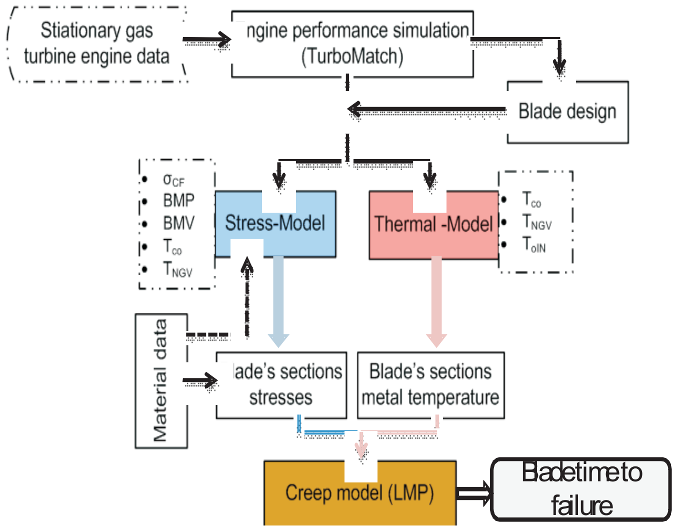

Figure 2 Creep model life assessment

3.2. *Thermal model*

An RTDF of gas temperature was used to calculate the temperature variation at each blade section. Typical values for the RTDF are 0.07 to 0.1 for the first rotor [1], [3], [4]. The location of the maximum temperature was based on the fact that the rotation of the turbine blade causes the peak gas temperature to shift from the mid–span of the blade toward the tip region [5]. Full details of the thermal model used in this paper are presented in [2].

3.3. *Creep model*

The creep life of the blade at each section of interest can be obtained as a function of the blade section stress and the blade metal section temperature using the LMP approach. The blade creep life varied at each blade section due to the changes in metal temperature and stress across the blade span. The lowest creep life of any individual blade section was considered to be the minimum blade life (ie the blade residual creep life).

4. Results and discussion

In the study, RTDF, TET, T_{amb} were all varied and different degrees of compressor (fouling) degradation were introduced. A reference baseline for TET, RTDF, ambient temperature and relative rotational speed (PCN) were set at 1500 K, 0.1, 288.15 K and 100%, respectively. The creep life at the root of the blade at these baseline conditions was taken as the reference creep life.

4.1. *Effect of RTDF on turbine blade creep life*

RTDF was varied from 0.07 to 0.1 (typical values for turbine rotor blades). The TET and ambient temperature were maintained at 1540K and 318.5K, respectively. The PCN remained at its baseline value. Figs 3 to 5 show the gas and metal temperature and creep life distribution along the span of the blade at the different RTDF values. In Fig. 3, as the value of RTDF is increased from 0.07 to 0.1, the maximum gas temperature increases from 1561K to 1584K at a point 75% along the span of the blade. However, lower RTDF values result in high temperatures at the root and at the tip of the blade. High temperatures at the root and tip are to be avoided since the root of a turbine blade bears the largest stresses, and at the blade tip there is a need to prevent blade expansion to maintain tip clearance.

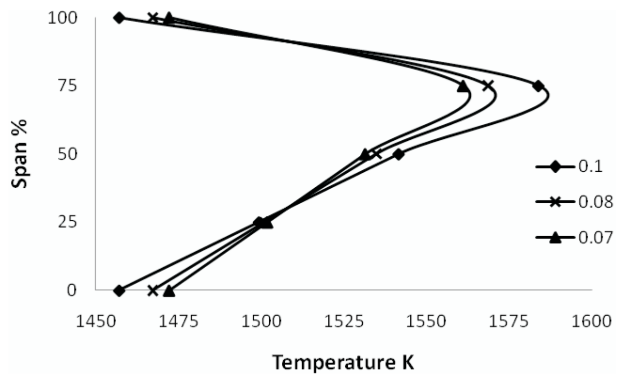

Figure 3 Combustor outlet temperature profile for TET of 1540 K and T_{amb} 318.15 K

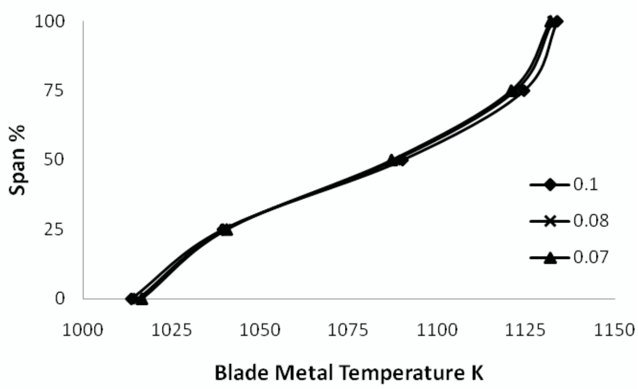

Figure 4 Blade metal temperature distributions along blade span at TET 1540 K and T_{amb} 318.15 K

Hence, for a given TET requirement, it would be necessary to choose an RTDF that gives lower temperatures at the root and tip of the blade for better creep life. Fig. 4 illustrates the blade metal temperature distribution across the span of the blade for different RTDFs. In all cases, the metal temperature increases progressively from the root to the tip of the blade. There is only a slight temperature increase of about 3K at the root of the blade and from mid span to the tip, as the RTDF increases. Nevertheless, this small increase in temperature has a significant impact on the creep life of the blade as shown in Fig. 5.

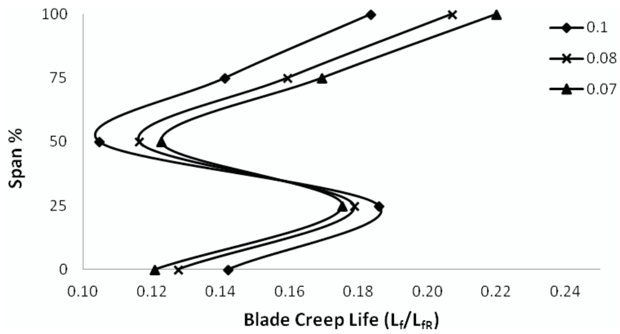

Figure 5 Blade creep life (Lf/LfR) along blade span at TET 1540 K and T_{amb} 318.15 K

In Fig. 5, the creep life at each blade section is presented relative to the reference creep life of the blade. However, three distinct locations can be identified that describe the variation of creep life along the span of the blade. From the root to 25% of the blade span, as the stress is reduced and blade metal temperature increased, the blade creep life is increased. This means that the blade creep life was driven by the reduction in the blade stresses. However, from 25% to the blade mid–span, the blade creep life was reduced as a result of the increase in the blade metal temperature; although the stress has been further reduced. This implies that the blade creep life in that location was driven by the greater effect of the increase in blade metal temperature. Above the blade mid–height, the creep life improves as a result of the greater effect of the reduction in the blade stresses. Creep life in this region is therefore dominated by the effect of low stresses.

It is also observed that the lowest relative creep life occurs at the blade mid–span for RTDF of 0.1 and RTDF of 0.08, while the lowest relative blade creep life for RTDF 0.07 occurs at the root. This indicates that the decrease in the effect of centrifugal force at 50% of the blade height was far greater than the temperature rise, hence affecting the position of the lowest creep life for RTDF 0.1 and 0.08. On the other hand, the effect of blade metal temperature rise is much higher for an RTDF of 0.07, hence the lowest creep life remains at the root which has the lowest blade metal temperature.

4.2. *Effect of turbine entry temperature on creep life*

The effect of increasing TET on the creep life at the blade root for different RTDF and ambient temperature of 288.15K is presented in Fig. 6. TET is represented as a relative value to baseline TET. There is a marked decrease in creep life as TET increases from the baseline, and a corresponding higher creep life as the TET is reduced. Taking RTDF of 0.1, a 3% increase in TET reduces the relative creep life from 1.0 (Rf in Fig. 6) to 0.3. This translates to a 70% reduction in creep life. Hence, the practice of over firing gas turbines to increase power output is highly detrimental to the creep life.

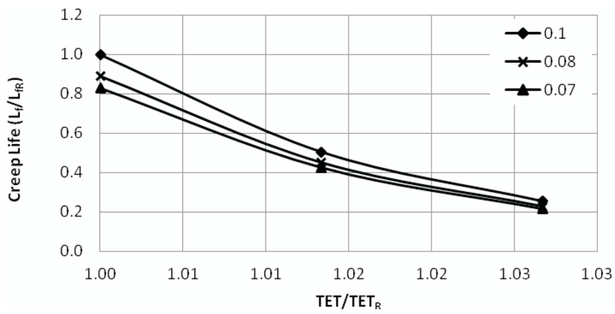

Figure 6 Blade creep life at the root for different RTDF at T_{amb} 288.15 K

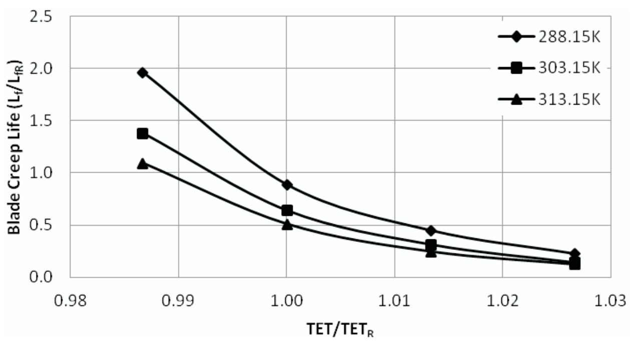

Figure 7 Blade creep life at different T_{amb} for RTDF 0.08

4.3. *Effect of change in ambient temperature on creep life*

The effect of change in ambient temperature on creep life was examined for a fixed RTDF of 0.08 and ambient temperatures of 288.15K, 303.15K and 313.15K. Fig. 7

shows that the creep life progressively reduces with the increase in ambient temperature. Operators of gas turbines in regions of high ambient temperatures should therefore optimize their operations for the most efficient power settings that will prolong their engines' creep life. Additional cooling, such as inlet water injection, could also be considered but there are cost implications. Furthermore, it can be observed from Fig. 7 that as the ambient temperature further increases, the rate of reduction in creep life becomes smaller with increases in TET beyond $\mathrm{TET}/\mathrm{TET}_R = 1.02$. This implies that at higher ambient temperatures, further increases in TET beyond the design point TET will have only a marginal effect on creep life. Thus, at these conditions, the value of TET will drive the creep life and not the changes in ambient temperature.

4.4. *Effect of compressor degradation on creep life*

Compressor fouling is recognized as the most common cause of engine performance deterioration [9]. It manifests as a build up of dirt on the compressor blades, thereby constricting the air flow passage, thus reducing mass flow capacity. There is also a reduction in efficiency due to the change in blade aerodynamic profile and increased surface roughness. The reduction in mass flow also leads to lower compressor pressure ratio due to the change in the compressor operating point on its characteristic. The result is a decrease in shaft power and increase in specific fuel consumption (SFC). Operationally, to recover the loss in power, the fuel flow could be increased leading to higher TET and decrease in creep life. In this study, three degradation cases are used to examine the effect of different levels of compressor fouling on creep life. These are: severe fouling, (representing the scale of compressor fouling in highly polluted environments), moderate fouling and light fouling as a result of normal usage. Tab. 3 details the percentage drop in mass flow capacity and efficiency for the cases examined. These values are consistent with typical values for compressor fouling [9]. For ease of reference, 3%, 2% and 1% are used to represent severe, moderate fouling and light fouling, respectively.

Table 3 Creep model life assessment

Compressor fouling	Change in Mass flow capacity (%)	Change in isentropic efficiency flow (%)	Designation
Severe	-6	-3	3%
Moderate	-4	-2	2%
Light	-3	-1	1%

In Figs 8 and 9, the effect of the different levels of fouling are compared with the baseline conditions. Fig. 8 shows that compressor fouling has no effect on the location along the blade span of the maximum and minimum creep life. Moreover the shape of the combustor outlet temperature distribution, shown in Fig. 9 is unchanged. Fig. 10 also shows that the trend in blade metal temperature remains the same. Hence, the only effect of increasing TET to regain performance due to compressor degradation is the severity in creep life reduction.

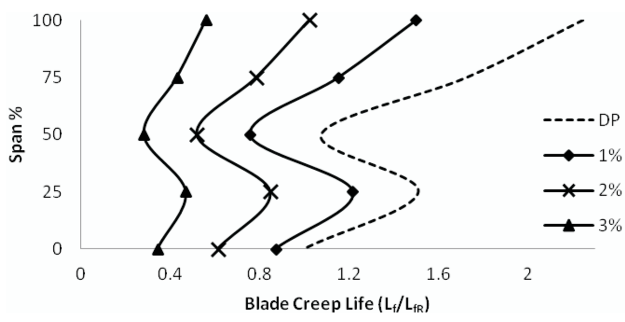

Figure 8 Blade creep life for compressor degradation at T_{amb} 288.15 K

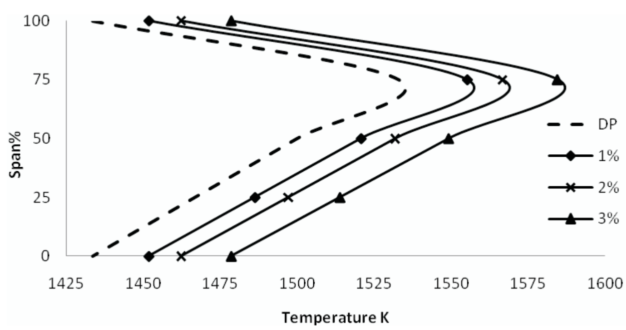

Figure 9 Combustor outlet temperature distribution compressor degradation at T_{amb} 288.15 K

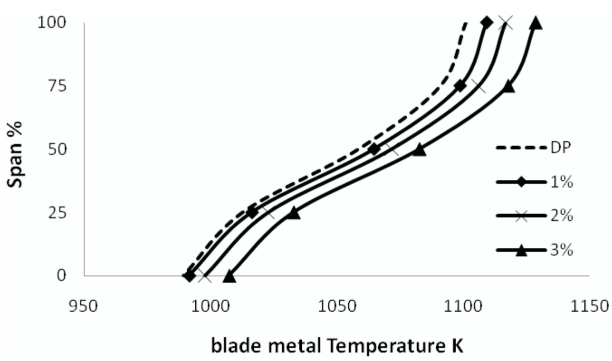

Figure 10 Blade metal temperature compressor degradation at T_{amb} 288.15 K

Fig. 8 shows clearly the reduction of creep life from a factor of 0.9 to a factor of 0.39 as the severity of fouling increases from 1% to 3% at the blade mid-height. Performance recovery can be achieved by either regular washing of fouled compressors or by increasing TET (thereby reducing creep life). Economic studies have suggested that compressor washing is the favoured solution to performance recovery.

5. Conclusions

This paper has investigated the effects of the design parameters and operating conditions on turbine blade creep life on a stationary gas turbine engine. The gas turbine engine model was developed and simulated at both design and off–design conditions using a thermodynamic performance model. Also, the first stage of the high pressure turbine blade was sized using a constant nozzle method in order to facilitate the estimation of creep life. Stress and temperature distributions along the blade span were estimated and used in a creep model to obtain the blade's residual creep.

The paper highlights how different operating conditions and design parameters can influence the location of the lowest blade creep life along the span of the blade. The effect of compressor fouling degradation on the blade creep life was also examined. The understanding of the relationship between design and operating conditions on creep life will enable gas turbine operators to make better informed decisions concerning maintenance and the economics of trading off performance for creep life.

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