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A Review on Thermal Paint on Turbine

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ABSTRACT

Temperature is a critical parameter in many engineering applications but it can be challenging to measure, particularly in situations where access is limited or the measurement is required on moving components. A pertinent example of this is the hot section of gas turbines. The operating temperature of a gas turbine is fundamental to its performance. The drive for improvements in thrust and efficiency have led to higher operating temperatures which have been made possible through the incorporation of cooling channels and Thermal Barrier Coatings (TBCs) on the critical components in the hot gas stream. Accurate temperature information is required in order to make full use of the thermal protection afforded by the TBCs to ensure safe operation and economic component service lives.The main challenge lies in noting the temperature of components which are subjected to repeated motion and this technique of temperature measurement is suitable mainly for gas turbines blades. Creep which is failure due to subjected stress at elevated temperature can be calculated by using thermal paint technique of temperature evaluation which certainly impacts the life of the turbine and the efficiency of performance. An attempt to define the parameters of further study on the platform of existing research is done in this present work.

Keywords:— *Thermal paint, NDT, Gas Turbine*

INTRODUCTION

The Nondestructive testing science is a broad field that covers variety of testing methods and applications, in addition to the associated pre and post processing mathematics. The diversity in the Nondestructive testing tools is only matched by its fields of application, which covers the testing of civil and mechanical structures and components. These include metallurgical and crystal temperature sensors. Both rely on permanent changes to the material structure caused by temperature exposure. The analysis of the thermally grown oxide by microscopy of sectioned samples is also used to infer the thermal impact but this is also an inherently destructive technique. A non-destructive technique is required which provides accurate temperature measurements which could be preferably be applied in-situ to avoid the high costs associated with disassembly of the engine. A novel technique was proposed by Feist et al. 14 which introduces optically active material into ceramics which make them luminescent. During thermal exposure the ceramics undergo permanent physical change which can be nondestructively detected and quantified by analysis of the luminescence.

II. THERMAL PAINT SENSING FOR GAS TURBINE BLADE.

Gas turbine components operating at elevated temperatures deform with time under the influence of applied stress. Ultimately, the accumulation of such deformation leads to fracture by a creep rupture mechanism. Gas turbine blade creep damage is the principal cause of blade life reduction for base loaded gas turbines. Consideration of these deformation and damage processes is a key part of critical component design assessment for high temperature applications, with the necessary engineering calculations requiring knowledge of creep-rupture properties for the material from which the structure is manufactured. Creep-rupture properties are determined from the results of a number of creep tests performed for a range of constant temperature and constant stress conditions. The key ingredient in power plant life extension is the remaining life extension of critical components such as gas turbine blades and the determination of blade creep and fatigue loading behavior under critical working conditions.

There are a large number of constitutive equations which can be used to represent material creep deformation characteristics ranging from simple phenomenological to complex physically based. No single constitutive equation effectively represents the creep deformation characteristics of all materials over their entire temperature application range. The effectiveness of a constitutive equation to model primary, secondary and/or tertiary creep deformation for specific applications can vary with material characteristics and source data distribution. In particular, not all model equations and fitting procedures are suitable for the prediction of alloy-mean long-time creep strength behavior.

Thermographic inspection refers to the nondestructive test in of parts, materials or systems through the imaging of the thermal patterns at the object's surface.[1 Strictly speaking, the term thermography alone, refers to all thermographic inspection techniques regardless of the physical phenomena used to monitor the thermal changes. For instance, the application of a temperature sensitive coating to a surface in order to measure its temperature is a thermographic inspection contact technique based on heat conduction where there is no infrared sensor involved.

Compressor blades and vanes are amongst the foremost components of the gas turbine engines and are damaged mainly either due to the strike of the birds or sand causing “Foreign Object Damage” (FOD), or because of the creep fatigue developed due to the operation in elevated temperature zones and cyclic loading (1 to 4).The impact of FOD is generation of cracks due to debris ingestion and vibrations caused because of alteration in aerodynamic flow over the blade airfoil and unbalancing of rotating components (1 to 5). On the other hand the creep and fatigue mechanism account for the major failures of compressor and turbine modules and are generated due to their exposure to a fluctuating and aggressive thermal environment. Creep damage results in reduction in the strength of the material due to formation of intergranular voids and subsequent cracking. Fatigue generates creeps due to continuous plastic deformation with clear evidences of triangular cracking. A specific attention has to be given to the fatigue caused due to high temperature while analysing the mechanical behaviour of the aero engine hot section components. Accurate design life and remaining life prediction is an important aspect of any gas turbine programme. Thermo mechanical fatigue (TMF) has been identified as a major cause of degradation and failure of gas turbine hot end components and there is as yet no generally accepted method for predicting the TMF behaviour of the material. In addition, an intimate knowledge of material behaviour like the creep formation, low and high cycle fatigue behaviour, oxidation and response to TMF is required. However complete characterisation of a material is costly, time consuming and therefore impractical where quick solutions to everyday operational problems are required. Figure (1) shows the damaged blades of a gas turbine. Extensive thermal mapping has to be done to detect any life issues at an early stage and ensure reliable performance in the harsh operating conditions.

Figure 1: Creep Failure of Turbine Blade

Apart from the predictive numerical thermal models, a series of experimentations are carried out to determine the maximum temperature attained during the operating conditions to keep it below the material limiting temperatures and also design an efficient cooling system. In order to trap the large temperature gradients on the new generation smaller engine components with complex geometrics and hard to access location innovative thermal sensors are required.

Conventional thermometry falls short to capture the true temperatures either due to contact friction or errors in transferring the data from measured moving parts with critical geometries to external read out units with a complex cable network. Moreover the data obtained is local temperature without any gradient. Further the inability to accurately understand the emission characteristics of different materials at different elevated temperatures, thermal analysis using optical pyrometry becomes quite challenging. The inherent property of the conventional sensors to interfere and affect the thermal conditions of the operating environment making them intrusive generates additional challenges. In such case the thermal paint is an effective substitute. Thermal paints are temperature sensing paints which change their color when exposed to elevated temperature. The paint exhibit different colors at different temperatures and produces a thermal paint contour on the surface of the heated component with the required thermal gradient. The color change is permanent and is roughly analysed by skilled human operators. The paint has 7-10 transformations temperatures where the change in color is prominent and can be perceived by the human eye. But this is not sufficient to analyze the performance of the operating component. Moreover the manual analysis is subjective and leaves much room for human error in analyzing the minute contrasts in the series of isothermal bands. A more detailed and reliable analysis is required to enhance the working life of the components.

The Temperature profiling of components in gas turbines is of increasing importance as engineers drive to increase firing temperatures and optimise component's cooling requirements in order to increase efficiency and lower CO_2 emissions. However, on-line temperature measurements and, particularly, temperature profiling are difficult, sometimes impossible, to perform due to inaccessibility of the components. A desirable alternative would be to record the exposure temperature in such a way that it can be determined later, off-line. The commercially available Thermal Paints are toxic in nature and come with a range of technical disadvantages such as subjective readout and limited durability. This paper proposes a novel alternative measurement technique which the authors call Thermal History Paints and Thermal History Coatings. These can be particularly useful in the design process, but further could provide benefits in the maintenance area where hotspots which occurred during operation can be detected during maintenance intervals when the engine is at ambient temperature. This novel temperature profiling technique uses optical active ions in a ceramic host material. When these ions are excited by light they start to phosphoresce. The host material undergoes irreversible changes when exposed to elevated temperatures and since these changes are on the atomic level they influence the phosphorescent properties such as the life time decay of the phosphorescence. The changes in phosphorescence can be related to temperature through calibration such that in -situ analysis will return the temperature experienced by the coating. A major benefit of this technique is in the automated interpretation of the coatings. The knowledge of accurate temperature profiles on critical hot gas path components is of highest importance when designing novel more energy efficient components for new generation gas turbines, boilers, fuel cells or furnaces. Further, the ability to identify components which have seen excessive heat during operation is highly desirable as it enables improved maintenance procedures and reduces the number of unplanned outages. The luminescent ceramic can be applied on a surface in two different ways. First, it can be embedded in a water based binder to form paint which is applied using a common air spray gun. Alternatively it can be applied using an industrial coating process called atmospheric plasma spraying (APS) which produces very robust and durable coatings for harsh environments. This new technique shows significant advantages over previous generations of temperature indicating systems (thermal crystals, thermocouples, thermal paints etc) in terms of toxicity, measurement time, accuracy, ease of use and other aspects of their implementation.

Four Thermal paint is a new, more efficient and cost effective temperaturesensing technology to replace current thermometry methods. The unique technology, patented by SCS, will be beneficial in all industrial sectors where temperature information is essential. The paint comprises luminescent sensor materials and a water based binder. When heated in operation, the luminescent properties of the sensor coating permanently change according to the temperature of exposure. After operation, an automated optical read-out device measures the luminescence to provide the maximum temperature of operation. The thermally activated changes occur over a wide temperature range so that a temperature profile can be measured without data gaps. The current operating range is 200-900°C with a precision of ±5-10°C.

Figure 2: Point of Application of thermal paint

Thermal history paints are composed of two materials, a phosphor powder and a high temperature binder. The europium (Eu) doped phosphor powder was synthesized in its amorphous state using a standard sol-gel preparation route. To monitor the quality of the phosphor product, it is characterized using x-ray diffraction and Fourier transform infrared spectroscopy.

To form a smooth paint, the phosphor powder needs to be homogenously mixed with a binder. Important requirements are, first, that the binder allows a paint to adhere to the surfaces of interest and can survive at the high temperatures likely to be encountered and measured. Secondly, the binder must not react with the active ingredient or negatively affect its sensing capability. There is a range of commercially available non-toxic silicate and silica based binders specifically designed for the preparation of paints intended to survive at high temperatures. A typical water based alkali silicate binder was found to be most compatible with the phosphors in terms of high temperature durability and surface adherence. A SRi Pro compliant smart / spot repair gravity feed spray gun was used for applying the thermal history paint to the stainless steel substrates. Spraying paint requires careful preparations and some experience in order to produce a smooth and uniform surface.

III. Literature Review

The conventional temperature measurement techniques including pyrometry and thermocouples have fundamental application limitations in the hot section of gas turbine engines. Extraneous radiation from reflections or particles in the gas stream causes significant errors in pyrometry results. Thermocouples require contact with the measured component and hence are intrusive and extremely difficult to practically apply, particularly on rotating components. Recent advances in phosphor thermometry have shown that accurate temperature measurements are possible on an operating gas turbine. However, the requirement for optical access is not always feasible during the engine operation. Several techniques have been developed which do not require optical access to the engine during operation. These techniques determine the operating temperature of the component after service due to the thermal history effects. The most prominent of these techniques is known as temperature indicating paint or ‘thermal paint’. This paint is applied on the components of interest which are then installed and run in the engine. Thermally activated chemical reactions between the metal elements and other molecules in the paint cause colour changes, due to permanent changes in the reflection spectra. The colour changes are then interpreted by a trained technician under controlled lighting in a laboratory and compared to calibration charts to determine the temperature of the exposure. Colour changes indicate isotherms across the component. The disadvantage with this technique is its subjective detection method, discrete measurements in contrast to continuous measurements, leaving gaps in the measurement range, and the limited durability of these paints.

Feist et al Thermal barrier sensor coatings – sensing damage and ageing in critical components

Sensing damage and ageing in critical components a range of applications are available for sensor TBCs. Degradation of the TBCs can be detected by introducing rareearth dopants. The extent of erosion damage can be quantified by imaging the phosphorescence emission. Chemical changes due to fuel contaminants clearly alter the emission properties. Furthermore, the monoclinic transformation which occurs after prolonged exposure at high temperature can be quantified using an intensity ratio technique. The operating temperature is a critical factor in degradation of the TBCs. Therefore, accurate temperature measurements are desirable to monitor the operating environment before damage occurs. The addition of dopant ions allows temperature measurements either during operation or off -line as a thermal history sensor. These embodiments of the sensor TBC have been successfully applied on gas turbines.

The temperature measurement can be done efficiently using thermal paint which can be done by online as well as offline method. It is preferable, though, to anticipate degradation before it occurs. As such, rather than detect the degradation itself, measurement of the cause of degradation would provide better information for life prediction. As stated earlier, the primary failure mode of TBCs is associated with the operating temperature at the TBC / bond coat interface. In operation, a balance must be reached between efficiency gains by increasing the TET and reduction in component life. A 130°C increase in TET has been reported to provide a 4% increase in engine efficiency which provides a huge saving in operating costs [31]. For example, a 1% improvement can save $20m in fuel over the life of a typical gas-fired 400-500MW combined-cycle plant [31]. A 51°C increase at the bond coat interface, however, can cause a 6-fold reduction in coating life [8]. Therefore, engine manufacturers require accurate temperature measurements to validate models and improve designs. Meanwhile, engine operators require temperature measurements to maximise efficiency while maintaining safe and reliable operation. The operating environment and conditions of TBCs make temperature measurement very challenging.

Figure 3: Component subjected to thermal paint

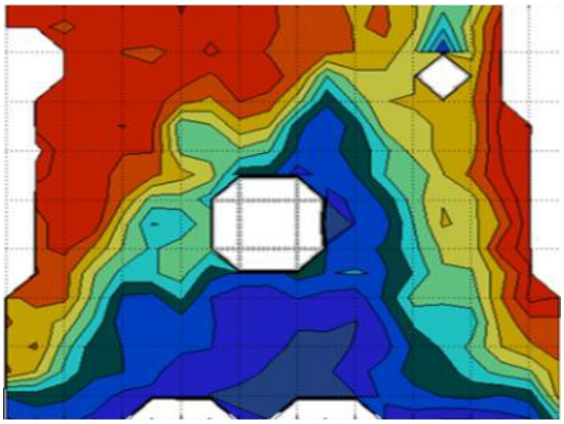

Figure 4. Thermal map of the component

Pankaj S. Mandavkar et al Study of Thermal Mapping for Health Monitoring of Gas Turbine Blade

For health monitoring of gas turbine blade, this presentation focuses on the effect of critical zone and hot spot along temperature distribution by using thermal paint. The computational flow and heat transfer results are also presented. This presentation includes unsteady high free –stream turbulence effects on film cooling performance with a discussion of detailed heat transfer coefficient and film cooling effectiveness distributions for standard and shaped film-hole geometry using the newly developed transient liquid crystal image method. The experimental set up constitutes of a fixture to hold the gas turbine blade. The gas turbine blade with internal cooling holes are painted with the thermal paint after proper surface treatment and fixed in the fixture. Hot compressed air through an LPG flame ignited through a nozzle fitted on a hand heater gun is allowed to impinge on the blade surface. The intensity of the hot air flow can be controlled by a regulating knob fitted on the gun holder. The component is heated for a predefined fixed heating time. It should be seen that the gun is properly fitted in its fixture so that the hot air is properly impinged in the required area. The component fixture is an oscillatory table which can oscillate the mounted components about a vertical axis so that the required surface area of the component can be exposed. A digital camera is mounted in position to capture the images of the thermal contours. The blade with application of thermal paint gives various temperature zone and distribution. That compare with blade without internal cooling holes. The component is heated for a fixed time exposing it to the elevated temperatures. As soon as the component starts heating the applied paint changes its color generating a contour of various colors embedded within with each color representing its respective temperature attained. The image of the thermal contour obtained is grabbed and given as an input to the Digital Image Processing algorithm which is developed for the Automatic Interpretation of the thermal paint data. The component is illuminated by a Xenon light source to avoid the unnecessary reflections and capture the true color profiles. The thermal paint is calibrate d by heating it at an interval of 150C and a calibration database file is generated which contains the various color profiles associated with their respective temperatures. The algorithm analyzes the image pixel wise and assigns every pixel with its corresponding temperature value by comparing it with the calibrated data thus generating a detailed and reliable thermal map of the components.

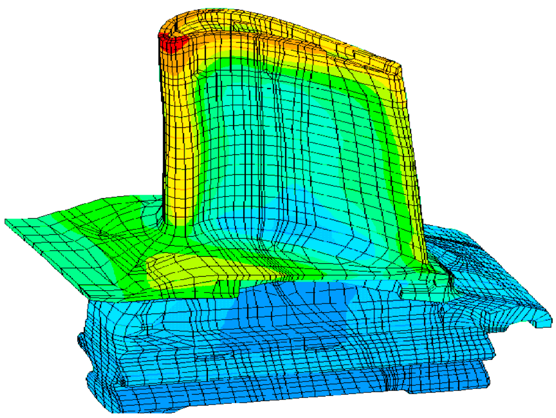

Figure 5. Contour of turbine blade using thermal paint.

A M Kempf Phosphor Based Temperature Indicating Paints

This research work reports the latest developments of a thermal history sensor based on phosphors that undergo permanent changes in their luminescence properties when exposed to high temperatures. Such thermal history sensors have several advantages over and address many of the shortcomings of existing sensors. The work contains details of the application of a phosphor-based temperature indicating paint based on *Y2SiO5:Tb* suspended in a chemical binder. The binder was found to influence the optical properties of the phosphor but despite this, a viable sensor paint for temperatures in the range 400°C to 900°C was formed. A thermal history coating was installed using a thermal barrier coating architecture, applied on various components of a *Royce-Rolls Viper 201* engine owned by *STS* and operated for a number of hours at *Cranfield University*. Post-operation analysis revealed a temperature distribution on the surfaces/ components and enabled hotspots to be identified. Overall the results suggest that phosphor-based temperature indicating paints have the potential to surpass the capability of existing paints.

The requirement for access to components *in-situ* and/or the ability to transmit data during operation are common problems for all on-line temperature measurement techniques. They are particularly acute in gas turbines and for this application a number of off-line temperature measurements have been developed. Here, the sensor is such that it undergoes permanent changes as a result of the temperature to which it is exposed and usually the duration of the exposure. The changes can be studied later off-line, quantified and hence the temperature of exposure deduced. In a sense such sensors have *memory* and as a result they are sometimes referred as *thermal history sensors*. The sensitivity to the duration of exposure is an important factor and, if temperature is the desired measure and, ways of decoupling its effect from that of temperature must be found. There are a number of sensors of this type available to the measurement engineer and some examples are given below. Metallurgical sensors comprise a metallic plug that is inserted into the component of interest by, for example, drilling and tapping a hole in it and screwing in a plug of the sensor material. The materials are carefully chosen to undergo changes in hardness, magnetic properties or phase composition at prescribed temperatures. Temperature measurements in the range 400-900°C are possible but the required exposure times are hundreds or thousands of hours. An obvious drawback of this technique is the requirement to embed the sensor in the component with the attendant risk that doing so will compromise its structural integrity.

M. F. Abdul Ghafir, Scholl of Engineering Gas Turbine" Performance Based Creep Estimation For Gas Turbines Application

According to Jacobsson, turbine blade cooling which is used to lower the turbine blade's temperature will induce high temperature gradients between the blades high and cold regions thus generating σ, and during service, the effect of variation results in TMF Fatigue, in this context, can be either mechanical or thermal-mechanical fatigue (TMF). Mechanical fatigue is a failure occurring under cyclic loading which is, for example, caused by vibration. on turbine blades during gas turbine start-stop cycle and power change. Mechanical fatigue can be further divided into two: high cycle fatigue (HCF), and low cycle fatigue (LCF). The distinction between them is where the repetitive application of load is taking place. HCF is categorized by high frequency and low amplitude elastic strain. An example of HCF will be when the turbine or the compressor blade is subjected to repeated bending, such as when the blade passes behind a stator vane, hence emerges into the gas path which will bend the blade due to high velocity gas pressure. This will force the blades to vibrate and the excitation at some point will match the blade's resonant frequency causing the amplitude of vibration to increase significantly LCF on the other hand is categorized by low frequency and high amplitude plastic strain. When dealing with LCF, the yield limit of the material is often exceeded and the material becomes plastic; therefore, repetitive plastic deformation is the main cause of LCF. Although there is no distinct border between the two types of failure, the traditional approach is to classify failures as HCF and those occurring below that value as LCF, TMF on the other hand occurs when the component is not only exposed to cyclic loads but is also experiencing variations in temperature gradient, resulting in significant thermal expansion and contraction. When gas turbine hot section components are being operated at extreme operating conditions, several damage mechanisms such as fatigue, high temperature corrosion/ oxidation, and creep deformation will inevitably emerge. The presence of such mechanisms will cause the component to lose its ability to sustain its intended function, increase its life consumption rate, and to some extent, will cause the component to fail prematurely.

Zdzislaw Mazur Evaluation of Creep Damage in a Gas Turbine First Stage Blade

This research work presents creep damage evaluation in the service exposed air cooled first stage blade 1100°C class of a gas turbine after 24000 operation hours. The blade is made of In conel 738 LC Nickel based superalloy. The gas turbine inlet temperature (TIT) is 1100°C. To get blade operational load, a thermo mechanical analysis was performed using the Finite Element Method (FEM) including centrifugal stresses and thermal stresses. Blade airfoil temperature distribution obtained from previous Computational Fluids Dynamics (CFD) analyses was used for thermal stress determination in the blade. The effect of multi-axial stresses has been taken into account. Using the thermo mechanical stress level value obtained and its distribution on the blade airfoil, some creep life prediction models were evaluated including the Norton-Bailey, Dorn-Bailey and Larson-Miller Parameter, comparing them to real bucket life. On the basis of results obtained, a new analytical model for gas turbine blade creep life prediction is proposed, which includes the influence of blade material ultimate tensile strength to reflect heat-to-heat variation in strength. The results obtained were validated to real bucket life and found in a good concordance to experimental creep data for an Inconel 738 LC super alloy.

Silvia Araguás Accelerated thermal profiling of gas turbine components using luminescent thermal history paints

This article describes the underlying principles behind this novel technology and the advantages it provides over existing state-of-the-art methods. The benefits will be demonstrated through measurements on nozzle guide vanes (NGVs), with the view to compare and validate them against thermocouple measurements. The results show that the THP extends the limited information from thermocouples to provide a more complete view of the thermal processes on the component. THPs are comprised of ceramic pigments in a binder matrix that can be applied to any hot component as a thin coating. These pigments are doped with optically active ions, which will phosphoresce when excited with a light source. The coating material experiences irreversible structural changes depending on the temperature it is exposed to. Nearly 400 measurement points were obtained for the pressure and suctions sides, as well as the shroud downstream and upstream. Thermocouple data revealed a significant difference in temperature between vanes. This was attributed partly to the non-uniform heat conduction through the metal parts of the test rig and partly to non-uniform heat distribution in the exhaust from the combustor. The results obtained through the THP supported the thermocouple readings and were able to further provide extensive thermal maps across surfaces including the shroud downstream, providing a clear indication of the hot gas stream path. The results showed that the THP extends the limited information from thermocouples to provide a more complete view of the thermal processes on the component.

Cleeton Blade cooling optimization in humidair and steam-injected gas turbines

Humidified gas turbine cycles such as the humidified air turbine (HAT) and the steam -injected gas turbine (STIG) present exciting new prospects for industrial gas turbine technology, potentially offering greatly increased work outputs and cycle efficiencies at moderate costs. The availability of humidified air or steam in such cycles also presents new opportunities in blade and disk cooling architecture. Here, the blade cooling optimization of a HAT cycle and a STIG cycle is considered, first by optimizing the choice of coolant bleeds for a reference cycle, then by a full parametric optimization of the cycle to consider a range of optimized designs. It was found that the coolant demand reductions which can be achieved in the HAT cycle using humidified or post-after cooled coolant are compromised by the increase in the required compression work. Furthermore, full parametric optimization showed that higher water flow-rates were required to prevent boiling within the system. This corresponded to higher work outputs, but lower cycle efficiencies. When optimizing the choice of coolant bleeds in the STIG cycle, it was found that bleeding steam for cooling purposes reduced the steam available for power augmentation and thus compromised work output, but that this could largely be overcome by reducing the steam superheat to give useful cycle efficiency gains.

Moussavi Torshizi Failure analysis of gas turbine generator cooling fan blades, Engineering Failure Analysis.

Since the optimum operation of a generator is highly affected by increasing in temperature, a cooling system is used to control the temperature. Employing a fan as a cooling system for the generator at the end sides of its rotor is a practical method [Montazer Ghaem Gas Turbine Power Plant. Gas turbine generator manual, Iran, 2004]. In some cases, fracture of blades causes short circuit between rotor and stator and consequently generator explosion and huge financial loss. Since fracture in cooling fan blades has been occurred five times in this case study, in this research, the emphasis has been placed on failure analysis and preventing methods from the fracture in this generator's fan blades. Survey and analysis of the above-mentioned problem have been conducted.

In order to study the imposed stresses of the fan blades due to operation, fan should be simulated. To do this, Computational methods were employed to analyze fluid flow, stresses and vibration. Separation phenomena and turbulent flow (vortex formation) might be the cause of vibration in fan's blades . Vibration due to oscillatory change of pressure distribution in two sides of blade, may cause blade fatigue . Therefore, our purpose for conducting CFD analysis is to achieve air velocity distribution around blades, study airflow lines (in order to observe probable vortex formation and related problems) and determination of force, resulted from air pressure over blades.

IV. OBJECTIVES

A thorough literature survey has revealed that a substantial amount of work has been carried out on non destructive testing of the gas turbine blade using various techniques such as online method of infrared technology using thermal paints and off line method again using the thermal paint but with visual inspection of pattern subjected variation in colour.

The various objectives of the proposed work can be enumerated as follows:—

- The turbine blade for gas turbine would be scaled down in size and subsequently subjected to thermal paint to facilitate the manufacturing of prototype.
- The whole model of turbine with reduced size will be modeled using CAD software.
- The values of parameters such as temperature can be used as boundary conditions to study effect of the same on turbine blade and calculate region of higher temperature using FEA software that is ANSYS.
- The method of approximate analysis is followed by experimental analysis of the prototype which uses a thermal painted blade and the region of high temperature would be identified

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