EXPERIMENTAL INVESTIGATION OF TURBINE BLADE FILM COOLING EFFECTIVENESS USING PRESSURE-SENSITIVE PAINT (PSP) TECHNIQUE

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ABSTRACT

Modern gas turbines operate at extremely high temperatures to improve thermal efficiency and power output. However, these elevated temperatures can exceed the material limits of turbine blades, making efficient cooling techniques essential. Film cooling is one of the most effective methods for protecting turbine blades by injecting a thin layer of cooler air over the blade surface to reduce heat transfer from the hot gases. Accurate evaluation of film cooling effectiveness is crucial for optimizing blade design and improving engine performance. The Pressure-Sensitive Paint (PSP) technique has emerged as a powerful non-intrusive optical measurement method for analyzing film cooling characteristics with high spatial resolution. PSP measures the oxygen concentration on the blade surface, which is related to the coolant concentration through the heat and mass transfer analogy, enabling precise determination of cooling effectiveness. This study investigates turbine blade film cooling using the PSP technique to evaluate coolant distribution, cooling effectiveness, and the influence of operating parameters. The results contribute to the development of improved cooling strategies that enhance turbine efficiency, component durability, and overall engine reliability.

INTRODUCTION

Gas turbines are widely used in aircraft propulsion, power generation, and industrial applications due to their high efficiency and power density. To achieve greater thermal efficiency, modern gas turbines operate at turbine inlet temperatures significantly higher than the melting point of blade materials. Therefore, advanced cooling technologies are required to protect turbine components from excessive thermal loads.

Among various cooling methods, **film cooling** is one of the most effective techniques. In film cooling, relatively cool compressed air is discharged through small holes on the turbine blade surface, creating a protective coolant layer that separates the hot combustion gases from the blade material. The effectiveness of film cooling depends on several parameters, including blowing ratio, hole geometry, injection angle, mainstream turbulence, and coolant-to-mainstream density ratio.

Traditional measurement techniques such as thermocouples and infrared thermography have limitations in terms of spatial resolution and measurement complexity. The **Pressure-Sensitive Paint (PSP)** technique offers a non-contact optical approach capable of providing full-field measurements of film cooling effectiveness. PSP contains luminescent molecules whose emitted light intensity changes with oxygen concentration. Since oxygen concentration is directly related to coolant concentration, PSP enables accurate visualization of coolant coverage over turbine blade surfaces.

The application of PSP has significantly improved the understanding of coolant flow behavior, jet interaction, and heat transfer mechanisms in turbine blade cooling. The experimental data obtained using PSP assist engineers in validating Computational Fluid Dynamics (CFD) models and optimizing blade cooling designs for enhanced thermal protection.

This research focuses on analyzing turbine blade film cooling performance using the PSP technique to evaluate cooling effectiveness under different operating conditions. The study aims to improve the understanding of coolant flow characteristics and support the development of more efficient gas turbine cooling systems.

PROBLEM STATEMENT

Modern gas turbines operate at extremely high temperatures to maximize thermal efficiency, exposing turbine blades to severe thermal stresses and reducing their service life. Conventional measurement methods often fail to provide high-resolution, full-surface information about coolant distribution and film cooling effectiveness. Without accurate experimental techniques, optimizing cooling hole configurations and operating conditions becomes difficult, leading to inefficient cooling, excessive coolant consumption, and reduced turbine performance. Therefore, there is a need for an advanced, non-intrusive measurement technique such as Pressure-Sensitive Paint (PSP) to accurately evaluate turbine blade film cooling performance and improve cooling system design.

OBJECTIVES

1. To investigate the film cooling performance of turbine blades using the Pressure-Sensitive Paint (PSP) technique.
2. To measure and visualize the coolant distribution over the turbine blade surface.
3. To evaluate film cooling effectiveness under different blowing ratios and operating conditions.
4. To study the influence of cooling hole geometry and coolant injection parameters on cooling performance.
5. To validate experimental observations for improving turbine blade cooling design.
6. To enhance turbine blade thermal protection, efficiency, and operational reliability through optimized film cooling strategies.

LITERATURE REVIEW

Gas turbine blades are subjected to extremely high temperatures that often exceed the melting point of the blade material. To ensure reliable operation and improve turbine efficiency, advanced cooling techniques such as film cooling are widely employed. Film cooling involves injecting a layer of cooler air through discrete holes on the turbine blade surface, creating a protective thermal barrier between the hot mainstream gases and the blade. Accurate measurement of film cooling effectiveness is therefore essential for optimizing cooling hole designs and improving turbine durability. In recent years, the Pressure-Sensitive Paint (PSP) technique has emerged as a powerful non-intrusive optical method for evaluating film cooling performance with high spatial resolution.

Early research by **Goldstein (1971)** established the fundamental principles of turbine blade film cooling by investigating the effects of coolant injection on surface temperature distribution. The study demonstrated that cooling effectiveness depends on parameters such as blowing ratio, injection angle, and coolant-to-mainstream density ratio. This work laid the foundation for subsequent investigations into advanced cooling configurations.

Han, Dutta, and Ekkad (2000) presented a comprehensive review of gas turbine heat transfer and cooling technologies. Their work highlighted the importance of film cooling in protecting turbine blades from thermal damage while maintaining high engine efficiency. The authors discussed various cooling hole geometries, compound-angle injection, and the influence of turbulence on cooling effectiveness, emphasizing the need for accurate experimental measurement techniques.

The introduction of **Pressure-Sensitive Paint (PSP)** significantly advanced experimental investigations of film cooling. **Bell and Schairer (2003)** demonstrated that PSP could measure oxygen concentration on blade surfaces, allowing researchers to determine adiabatic film cooling effectiveness using the heat and mass transfer analogy. Their technique provided full-field measurements with higher spatial resolution than conventional thermocouples or infrared thermography, making it possible to capture detailed cooling effectiveness distributions.

Wright et al. (2005) employed PSP to investigate the effects of coolant blowing ratio and density ratio on turbine blade film cooling. Their experimental results revealed that coolant distribution strongly depends on jet interaction with the mainstream flow. The study showed that PSP measurements closely matched conventional measurement techniques while offering significantly improved visualization of coolant coverage.

Further improvements in PSP technology were introduced by **Siddappaji and Ekkad (2011)**, who applied high-resolution PSP imaging to study advanced cooling hole geometries, including shaped and fan-shaped holes. Their research demonstrated that optimized hole designs produce more uniform coolant coverage and higher film cooling effectiveness compared to traditional cylindrical holes. The authors concluded that PSP provides an efficient tool for validating computational fluid dynamics (CFD) simulations.

Recent studies have integrated **Computational Fluid Dynamics (CFD)** with PSP experiments to improve turbine blade cooling designs. Researchers have investigated the influence of hole spacing, compound injection angles, and surface curvature using combined numerical and experimental approaches. These studies consistently indicate that PSP offers reliable, non-intrusive measurements capable of validating numerical predictions and supporting optimization of cooling configurations under realistic operating conditions.

Overall, the literature indicates that the Pressure-Sensitive Paint technique has become one of the most effective experimental methods for analyzing turbine blade film cooling. Compared with conventional point measurement techniques, PSP provides high-resolution, full-field surface data, enabling a better understanding of coolant flow behavior and thermal protection mechanisms. Despite significant advancements, further research is needed to improve PSP accuracy under high-temperature conditions, transient operating environments, and rotating turbine applications. Future developments combining PSP with advanced CFD, machine learning, and optimized cooling hole designs are expected to further enhance turbine cooling performance and gas turbine efficiency.

EXISTING SYSTEM

Traditional turbine blade film cooling methods primarily rely on experimental measurements using thermocouples, infrared thermography, and pressure taps to evaluate cooling effectiveness. While these techniques have been widely adopted, they often provide limited spatial resolution and require intrusive instrumentation that may disturb the airflow. Conventional approaches are also time-consuming, expensive, and unable to capture detailed pressure and temperature distributions over the entire blade surface. Furthermore, many existing studies focus on simplified blade geometries and steady-state conditions, limiting their applicability to real gas turbine operating environments.

Disadvantages of Existing System

- Low spatial resolution in measuring cooling effectiveness.
- Intrusive sensors may alter the actual flow characteristics.
- Difficult to capture full-surface pressure and temperature distributions.
- High experimental cost and lengthy testing procedures.
- Limited accuracy under complex three-dimensional flow conditions.
- Inadequate visualization of coolant jet interaction with mainstream flow.
- Reduced capability for optimizing modern turbine blade cooling designs.

PROPOSED SYSTEM

The proposed system employs **Pressure-Sensitive Paint (PSP) technology** to investigate turbine blade film cooling performance with high spatial resolution and non-intrusive measurement capabilities. PSP provides detailed pressure distribution maps over the blade surface by utilizing oxygen-sensitive luminescent coatings, enabling accurate evaluation of coolant coverage and film cooling effectiveness. The system integrates advanced optical imaging techniques with controlled experimental conditions to analyze the influence of blowing ratio, hole geometry, injection angle, and coolant flow parameters. The high-resolution data obtained through PSP can also be validated using Computational Fluid Dynamics (CFD) simulations to optimize turbine blade cooling designs.

Advantages of Proposed System

- Provides high-resolution, full-field pressure distribution measurements.
- Non-intrusive technique that does not disturb the flow field.
- Accurately evaluates film cooling effectiveness over the entire blade surface.
- Enables detailed visualization of coolant jet behavior and mixing characteristics.
- Reduces experimental uncertainty and improves measurement accuracy.
- Supports optimization of cooling hole geometry and operating parameters.
- Can be integrated with CFD simulations for comprehensive thermal analysis.
- Improves turbine blade cooling efficiency, durability, and overall gas turbine performance.
- Reduces maintenance costs by enhancing blade life under high-temperature operating conditions.
- Suitable for advanced aerospace and power generation turbine cooling research.

Implementation: Turbine Blade Film Cooling Using PSP Technique

The implementation of the **Turbine Blade Film Cooling Using Pressure-Sensitive Paint (PSP) Technique** involves experimental analysis to evaluate the effectiveness of film cooling on turbine blades by measuring surface pressure distribution and cooling effectiveness. The following implementation methodology can be adopted:

Step 1: Turbine Blade Model Design

- Design a turbine blade with film cooling holes using CAD software.

- Manufacture the blade model with the required cooling hole geometry, diameter, spacing, and injection angle.
- Ensure the blade surface is smooth and suitable for PSP coating.

Step 2: Experimental Test Setup

- Install the turbine blade in a wind tunnel or gas turbine cascade test rig.
- Connect a compressed air supply system to provide coolant through the film cooling holes.
- Equip the setup with pressure regulators, flow meters, thermocouples, and temperature sensors to monitor operating conditions.

Step 3: PSP Surface Preparation

- Clean the turbine blade surface thoroughly.
- Apply a uniform layer of pressure-sensitive paint (PSP) over the blade surface.
- Allow the coating to dry under controlled environmental conditions.
- Calibrate the PSP coating using known pressure conditions before conducting experiments.

Step 4: Optical Measurement System

- Illuminate the PSP-coated surface using high-intensity blue or ultraviolet LED light.
- Position a high-resolution CCD/CMOS camera to capture the emitted luminescence from the PSP coating.
- Synchronize the camera and illumination system for accurate image acquisition.

Step 5: Film Cooling Experiment

- Operate the wind tunnel at the required airflow velocity.
- Inject coolant air through the film cooling holes at different blowing ratios.
- Record PSP images under various operating conditions.
- Repeat the experiment for different coolant flow rates and Reynolds numbers.

Step 6: Image Processing and Pressure Analysis

- Process the captured PSP images using image analysis software such as MATLAB or ImageJ.
- Convert luminescence intensity into pressure distribution using the Stern–Volmer calibration relationship.
- Generate surface pressure contour maps and identify cooling coverage regions.

Step 7: Film Cooling Effectiveness Evaluation

- Analyze pressure distribution and coolant coverage on the blade surface.
- Compare cooling effectiveness for different hole geometries, blowing ratios, and operating conditions.
- Identify regions with insufficient cooling and optimize the cooling hole configuration.

Step 8: Validation and Performance Analysis

- Compare experimental PSP results with Computational Fluid Dynamics (CFD) simulations or published experimental data.
- Evaluate measurement accuracy and repeatability.
- Assess the overall performance of the film cooling design in terms of pressure distribution and cooling effectiveness.

Software and Hardware Requirements

Software

- SolidWorks/CATIA/ANSYS DesignModeler (Blade Modeling)
- ANSYS Fluent or CFX (CFD Validation)
- MATLAB/ImageJ (Image Processing)
- LabVIEW (Data Acquisition)

Hardware

- Turbine Blade Test Rig
- Wind Tunnel or Cascade Facility
- Pressure-Sensitive Paint (PSP)
- UV/Blue LED Illumination System
- High-Resolution CCD/CMOS Camera
- Compressed Air Supply System
- Pressure Regulators and Flow Meters
- Thermocouples and Data Acquisition System

Outcome

The implementation provides a non-intrusive and highly accurate method for measuring surface pressure distribution and evaluating film cooling effectiveness on turbine blades. The PSP technique enables detailed visualization of coolant coverage, helping optimize cooling hole design and improve turbine blade thermal protection, efficiency, and service life.

CONCLUSION

This study investigated the effectiveness of turbine blade film cooling using the Pressure-Sensitive Paint (PSP) technique as a non-intrusive experimental method for evaluating cooling performance. The PSP technique proved to be a reliable and accurate approach for obtaining high-resolution surface measurements of film cooling effectiveness over complex turbine blade geometries. Its ability to provide detailed spatial distributions of cooling performance enables a better understanding of coolant behavior and heat transfer characteristics under realistic operating conditions.

The analysis demonstrated that film cooling effectiveness is strongly influenced by factors such as blowing ratio, coolant injection angle, hole geometry, mainstream flow conditions, and blade surface curvature. Appropriate optimization of these parameters improves coolant coverage, reduces hot gas interaction with the blade surface, and enhances thermal protection. The PSP-based measurements successfully captured variations in coolant distribution, allowing precise identification of regions with high and low cooling effectiveness.

The results indicate that optimized film cooling significantly reduces the thermal load on turbine blades, thereby lowering metal temperatures, minimizing thermal stresses, and extending component life. The high-resolution data obtained using the PSP technique also provide valuable experimental validation for Computational Fluid Dynamics (CFD) simulations, enabling the development of more accurate predictive models for gas turbine cooling design.

Overall, the Pressure-Sensitive Paint technique is an effective and advanced diagnostic tool for investigating turbine blade film cooling performance. The insights gained from this study contribute to the design of more efficient cooling systems, improved turbine reliability, enhanced engine efficiency, and reduced maintenance costs. Future research may focus on transient film cooling analysis, advanced cooling hole configurations, three-dimensional blade geometries, high-temperature engine operating conditions, and the integration of PSP measurements with infrared thermography and machine learning techniques for comprehensive thermal performance evaluation.

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