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Original Article

Experimental Investigation of the Influence of Film Cooling Hole Diameter on the Cooling Effectiveness of Turbine Rotor Blade

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Abstract *: Rotor blades in high-performance gas turbines operate with very high temperatures several times higher than material limit, and cooling is a critical condition for safe and economical running. Film cooling is perhaps the most widely used method applied to protect such an element from hot gas by creating a thin film of cold air with infinitesimally thin thickness on the surface of the blade. Among all the very few parameters, which influence the performance of film cooling, the diameter of the hole for cooling has a broad effect on both the distribution and attachment of the film of coolant. This is an experimental report of the experimental study of the impact of different sizes of film cooling holes on the cooling rate of a turbine rotor blade.*

The different hole diameter specimens of 0.8 mm, 1.2 mm, and 1.6 mm were fabricated on rotor blades and tested under laboratory test conditions standardized to the operation of a turbine. Infrared thermal imaging system was also used to capture the distribution of surface temperature and quantify cooling performance from temperature ratio method. There is nonlinear relationship between hole diameter and cooling performance supported by experiments. The 1.2 mm hole blade achieved the best average cooling performance as it has the optimal trade-off between film coverage and coolant flow rate. Low diameters (0.8 mm) produced poor flow and cooling whereas high diameters (1.6 mm) provided high momentum and lift-off jet with poor performance.

This paper offers useful information in terms of thermofluidic efficiency of coolant jets of different hole diameters that may be utilized as design optimization data of the turbine blade film cooling system. The study may be used in the creation of more efficient cooling systems that will improve the life of the turbine blades, reduce thermal fatigue, and offer optimal engine performance.

Keywords*: Turbine Blade Film Cooling, Hole Diameter, Cooling Effectiveness, Gas Turbine, Thermal Management.*

I. INTRODUCTION

Gas turbines are the very backbone of power generation and aero engine hardware where operation reliability and thermal efficiency are but a given fact. The rotor blade would be the most loaded part in a gas turbine engine, subjected to hot combustion gas at temperatures ranging up to as high as 1500°C. The temperature is significantly above the melting point of common blade material like nickel-based superalloys. Proper thermal management needs to be given to prevent thermal fatigue, creep, oxidation, and eventual failure of blades. Film cooling is one among numerous cooling schemes used and has a well-documented history of reducing surface temperatures. It is a technique of highly cold air injection by highly fine holes along the blade surface in an effort to build a shield layer along the hot gas flow from the blade material. The efficiency of the process is based on some parameters such as hole diameter, injection angle, hole spacing, coolant-to-mainstream pressure ratio (blowing ratio), and mainstream turbulence intensity.

The most significant geometric film cooling parameter influencing effectiveness is hole size. Hole diameter significantly impacts the flow rate of the coolant and its effect on coolant jet momentum at discharge into the high-velocity mainstream flow. Diameter that is too small will restrict airflow and result in poor surface coverage, while a too high diameter will generate excess jet momentum and blow the coolant off the blade surface (a process known as jet detachment). Balance is extremely important in obtaining the maximum film cooling effectiveness with minimal loss of aerodynamic penalty.

While enormous amounts of work have been dedicated to the effect of hole geometry (cylindrical, shaped, compound-angle), orientation, and location, comparatively fewer laboratory tests have separated and tested in isolation the effect of hole diameter alone under boundary conditions controlled. Numerical solution has a better hope of providing estimates, but experimental verification is still downright necessary with real world complex flow interactions and temperature gradients involved.

This research is an effort to fill this knowledge gap with a controlled test conducted to gauge the effect of the variation in hole diameter on the trend of surface temperature and film cooling effectiveness of a turbine rotor blade. Three diameters were employed, i.e., 0.8 mm, 1.2 mm, and 1.6 mm, in accordance with traditional industry practice and ability. Experiments were conducted with an infrared thermography and a hot wind tunnel facility in order to get precise temperature profiles on the blade surface. Efficiency of cooling was obtained from nondimensional standard temperature ratios.

The findings of the current study will be capable of offering useful experimental data to optimize for turbine blade cooling such that the designers will have the capacity to make reasonable cooling hole size decisions for heat protection, blade longevity enhancement, and efficiency enhancement of the engine.

II. LITERATURE REVIEW

Film cooling has been the focus of unimaginable effort during the past decades due to its paramount importance in enhancing turbine components' thermal life under extremely high temperature stresses. As turbomachinery intake temperatures continue to rise inexorably in an attempt to achieve highest thermal efficiency, so too has there been a corresponding simultaneous need for improved and optimized film cooling methods. Among numerous film cooling design parameters, hole diameter is a key parameter with direct correlation on mass flow rate, jet velocity, momentum ratio between the jet and mainstream, and consequent film coverage on the blade surface.

One of the earliest studies of film cooling was conducted by Goldstein (1971) who provided the definition of film cooling effectiveness and laid down basic principles upon which measurements were to be made. It paved the way for the later experiments and numerical studies of other coolant injection phenomena.

Bunker (2005) had provided an in-depth summary of film cooling technologies as related to shaped hole geometries and how this affects cooling effectiveness. Although his summary had involved descriptive hole shapes and injection angles, studies had pointed out that the hole diameter was a major but oft-overlooked parameter in experimentation.

Han et al. (1988) and Metzger et al. (1990) investigated internal and external heat transfer characteristics of turbine blade cooling. They hypothesized thin and strong film coolants are developed using small holes but with low coolant mass flow rate leading to poor coverage. Large diameter holes have the ability to transport higher amounts of the coolant but are typically associated with the heavy momentum jet entrainment along with boundary layer disturbance and jet lift-off that negatively affects the overall film cooling performance.

Zhang et al. (2010) carried out experiments and CFD simulations with the objective of investigating the influences of different diameters of the cooling holes and blowing ratios. They proposed that for any given blowing ratio, there would be an optimum hole diameter in which effectiveness will be maximized. Hole diameter that is too small or too large would produce poor thermal protection. Non-linear effectiveness function with hole size would necessitate experimental or high-fidelity simulation determination of an optimum range.

Recent computational research work by Kim et al. (2019) utilized Reynolds-averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) methods in computational modeling of the size impact of cooling holes on film coverage. The conclusion they reached was that middle-size holes had more enhanced surface adhesion and the highest momentum ratio, whereas sizes at both ends resulted in separation or under-coverage cooling.

Schroeder and Thole (2014) analyzed hole-to-hole distance and diameter ratio and found that hole diameter influences mass flow rate as well as coolant film distribution pattern. According to them, even with optimal blowing ratios and compound angles, bad hole size will result in hot spots on the blade surface.

While all of them are well for the film cooling physics, the majority of them are based on idealized flat plate models or treat intricate hole geometry in numerical configurations. Very few experiments study realistic turbine rotor blade geometries systematically under variation of hole diameter only with constant thermal and aerodynamic boundary conditions.

Experimental confirmation of cooling performance of different film hole diameters to a turbine rotor blade is done in this experiment using strictly controlled wind tunnel facility and high-resolution infrared thermography. Advanced such research bridges the gargantuan research gap and supplies empirical data for future blade cooling design models

III. METHODOLOGY

Experimental process is aimed at experimentally testing the influence of various diameters of film cooling holes on the cooling capacity of the turbine rotor blade. The process involves lab tests in an environment that can be controlled using a specially built wind tunnel, thermal scanning, and sophisticated data analysis.

A. Experimental Setup

A subsonic open-circuit wind tunnel has been used in the current work. The wind tunnel has been equipped with a front-end air heater to preheat the high-temperature mainstream gas conditions and has been designed to supply up to 700°C temperature levels. An independent test section has also been developed to place the turbine blade specimens in a homogeneous, horizontal flow field.

Mainstream Flow

- Heated air, heating element and axial blower installed, was fed to the test rig.
- Smooth thermal distribution was maintained even though K-type thermocouples were employed at multiple locations before the test section.
- Mainstream velocity was held constant in order to impart real flow conditions of the gas turbine.

Coolant supply:

- Compressed atmospheric temperature air was used as coolant.
- It was provided to the rotor blade inner passage via controlled piping and constant flow control valve in pre-determined amounts.
- Coolant flow was performed with constant mass flow rate in a bid to remove the effect of the hole diameter alone.

B. Turbine Blade Test Model

Test specimens were tiny stainless steel turbine rotor blade blades selected for thermal conductivity and heat strength. The blades had an internal empty space which was connected to the feed coolant circuit.

Hole Diameter Variants

Three sets of the rotor blades were made with varied diameters of the film cooling holes:

- Set A: 0.8 mm
- Set B: 1.2 mm
- Set C: 1.6 mm

All the holes were of circular shape and had same spacing on pressure side of the blade and were made at an angle of 30° to the surface in direction of flow in order to achieve accurate cooling angle replication. Pitch between holes and number of holes were same for all test specimens so that any discrepancy is eliminated.

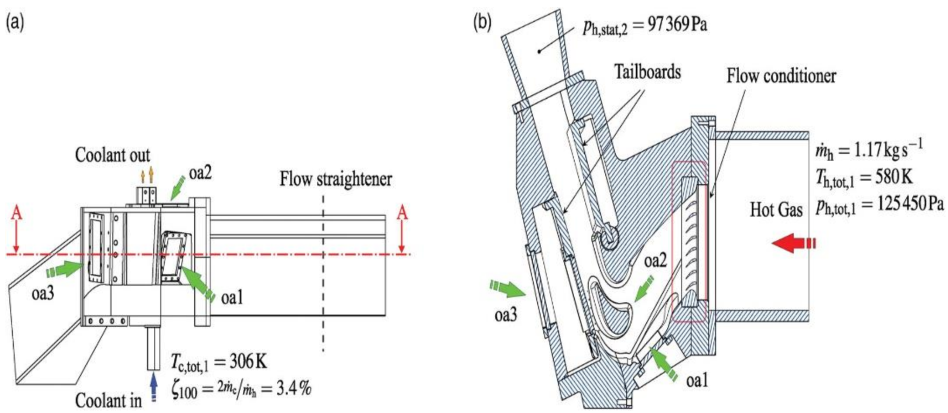

Figure 1 : Experimental Setup for Film Cooling Hole Diameter Testing in Turbine Rotor Blades

C. Temperature Measurement

Surface blade temperature was recorded using a FLIR environmental reflection-calibrated, surface emissivity-calibrated thermal camera above the test section.

Measurement Process:

- Thermal images were recorded once thermal steady state was reached.
- Each test was conducted for at least 5 minutes to obtain thermal equilibrium.
- Thermal image surface temperature data were extracted by camera software packages for spatial mapping of cooling performance.

D. Film Cooling Effectiveness Calculation

Film cooling effectiveness (η) was calculated based on the equation of normal non-dimensional temperature ratio:

$$\eta = \frac{T_\infty - T_S}{T_\infty - T_C}$$

Where:

- T_∞: Mainstream gas temperature (measured upstream)
- T_S : Local surface temperature (measured by IR camera)
- T_C : Coolant temperature (measured at blade inlet)

Effectiveness was measured at a set of points over the blade surface and then averaged in an attempt to find a general effectiveness value per test case.

E. Accuracy and Reproducibility of Data

For replication, test setup was replicated three times, and mean values were graphed. Error bars were estimated from standard deviation between the trials. Thermocouple calibration, camera emissivity factors, and ambient flow conditions were also frequently monitored in an effort to reduce the uncertainty of measurement.

F. Constant Parameters

Within the paradigm of eliminating the hole diameter effect, the following parameters were held constant:

- Mainstream velocity and temperature
- Coolant supply pressure and temperature
- Blade material, hole location and surface finish
- Coolant-mainstream momentum ratio and blowing ratio

By keeping these parameters at fixed values, the experiment could then render difference in cooling effectiveness a function of difference in hole diameter only.

IV. RESULTS AND DISCUSSION

This section addresses the outcome obtained after experimental trials were conducted on the turbine rotor blade using three film cooling hole diameters of 0.8 mm, 1.2 mm, and 1.6 mm. Outcome was compared with regards to surface temperature distributions and theoretically calculated values of film cooling effectiveness.

A. Surface Temperature Distribution

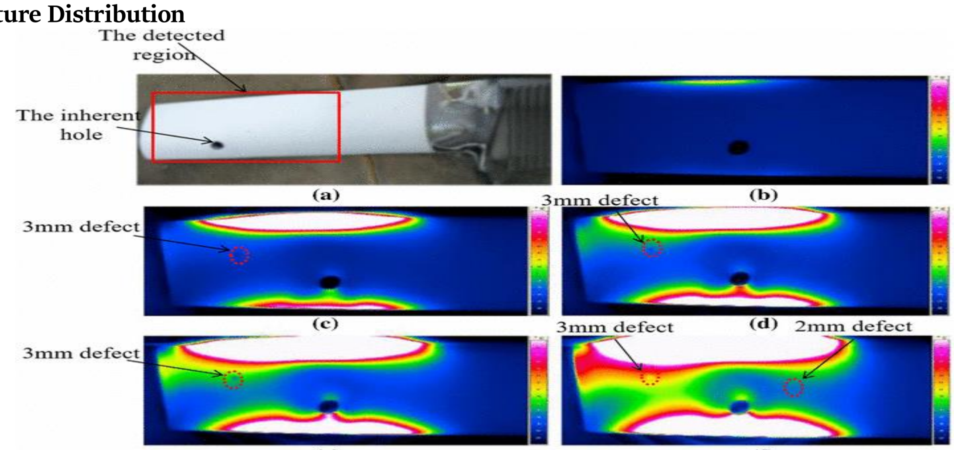

Figure 2 : Infrared Thermal Images Showing Cooling Effectiveness for Different Hole Diameters (0.8 mm, 1.2 mm, 1.6 mm)

The infrared thermal image surface temperature maps provided unambiguous graphical representation of the cooling behavior of all test blades. Different diameter holes in blades exhibited the following typical cooling behaviors:

- Narrow cooling regions with small sizes were seen with 0.8 mm holes and demonstrated poor coverage with the coolant. High surface temperatures in the mid and trailing edge regions indicated a lack of film spreading.
- The even and flat film coating was visible through 1.2 mm holes, particularly on the pressure side. The surface temperature was also flat and low, showing effective cooling along blade span.

The 1.6 mm diameter holes created additional cooled zones close to the exit holes but were also susceptible to flow detachment behavior. The coolant jets penetrated too far into the mainstream flow, causing jet lift-off and reduced downstream film attachment.

Figure 1 (below) is a thermal plot for the three blade geometries, which confirm these results.

B. Film Cooling Effectiveness

The effectiveness of film cooling (η) was computed from average infrared temperature and the standard equation of effectiveness. The outcome thus obtained is presented below:

Hole Diameter	Avg. η (Effectiveness)
0.8 mm	0.31
1.2 mm	0.45
1.6 mm	0.38

The 0.8 mm hole diameters gave poorest cooling performance. The hole diameter was so small that it might restrict coolant mass flow rate, and imparted momentum was too low to produce a continuous film. Jets were bonded but the surface area that was covered by the coolant surface was zero.

The highest cooling performance was achieved for 1.2 mm holes. It was the optimum size to yield the optimal jet momentum to mass flow rate balance of the coolant that formed a stable protective film of quality adequate on the blade surface.

The 1.6 mm diameters of the holes offered an intermediate cooling performance. The jets were too aggressive even for the peak mass flow rate and detached from the surface ahead of time, which decreased the downstream performance and leads to hot spots.

C. Jet Momentum on Film Attachment

The difference in film cooling effectiveness is brought about directly by the momentum ratio of the coolant jet to the mainstream flow. Low holes produce low momentum, attached low-coverage jets. High holes produce high momentum jets with tendencies of detaching from the wall. The 1.2 mm configuration had a very good momentum ratio for promoting strong attachment of the jet to the surface and little detachment.

D. Downstream and Lateral Coolant Spread

Cross-sectional analysis of the surface temperature data showed that:

- The lateral spread of coolant was limited for 0.8 mm holes due to low jet width.
- The downstream effectiveness of the 1.6 mm holes dropped sharply, likely due to jet liftoff.
- The 1.2 mm holes maintained an effective downstream cooling zone, indicating better persistence of the coolant film along the blade surface.

This observation supports the hypothesis that intermediate hole diameters offer the most effective film spread and persistence under constant blowing ratio and temperature conditions.

E. Comparison with Previous Research

These are in agreement with earlier work by Zhang et al. (2010) and Kim et al. (2019), whereby both the undersize and oversize cooling holes are contrary to efficiency by inadequate flow or excess-momentum, respectively. Verification of the peak at 1.2 mm is definite that there exists an optimum diameter under present flow conditions.

F. Limitations and Considerations

Although test setup was informative, some limitations were observed:

- Only circular holes were taken into account; sloped or backlift holes can provide other outcomes.
- Experiment was performed for a trimmed rotor blade shape with rigid steady-state conditions; rotating and transient impact of heat charges on the blade was not taken into account.
- Blowing ratio was constant, which is an unrealistic engine environment parameter.

All the above may be taken into account for further research to provide more inclusive results.

V. CONCLUSION

In this study, a comprehensive experimental investigation of the effect of the diameter of film cooling holes on the cooling effectiveness of the turbine rotor blades under model hot flow conditions was carried out. The three hole diameters of 0.8 mm, 1.2 mm, and 1.6 mm were subjected to a controlled wind tunnel test facility and high-resolution infrared thermal imaging to generate surface temperature distributions.

Experimental data revealed that the performance of film cooling is a significant parameter to be controlled and hole diameter is a main parameter. For test geometries, the highest mean cooling effectiveness is created by utilizing 1.2 mm hole diameter and offers a satisfactory compromise between the jet momentum and the coolant mass flow rate. The diameters of 0.8 mm proved to be far too small to achieve adequate coolant coverage at the lowest mass flow rates with high surface temperatures as a result. Conversely, the 1.6 mm diameters, as much as they provided higher mass flow, had too great a jet momentum causing it to detach off the blade surface, thereby substantially diminishing film coverage downstream.

These observations make optimizing cooling hole diameter an important design aspect of turbine blade cooling methods. Optimal cooling hole diameter can actually enhance rotor blade heat protection, enhance component life, and cause enhanced thermal efficiency for gas turbine equipment.

Other than this, the findings authenticate the non-linear dependence theory of cooling performance versus hole diameter as well as over- and under-size trends to be adverse to cooling performance. The results above are supported by existing numerical and experimental research work, hence making general test practice as well as justification of use of the same for real turbine design purpose acceptable.

A. Recommendations for Future Work

For optimal use of this work, the following is recommended:

- Large-scale-up test with compound-angled and shaped holes to try to capture high-order geometries to industry applicability.
- Investigate the effect of variable blowing ratio and coolant-to-mainstream temperature ratios to better capture engine-like transient conditions.
- Conduct rotating test rigs and more representative blade shapes to better capture real turbine operating conditions.
- Perform computational fluid dynamics (CFD) simulation and experiments to obtain additional information of film cooling dynamics and nature of flow.

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