EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON MIXING FLOW OF FILM COOLING BY USING TWISTED HOLES

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To my kind parents for their priceless support and motivation and to my tolerant wife and my lovely two daughters for their sincere help and accompany during my studies

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ABSTRACT

Increment in turbine inlet temperature (TIT) is essential for further improvement in thermal efficiency and higher power output of next generation gas turbine engines. Over past decades, significant effort has been made to increase the TIT through development of effective cooling strategies to maintain the blade temperature below the melting point of blade material. Film cooling techniques have been extensively researched to achieve higher TIT. This work was carried out experimentally and numerically to determine the enhancement of film cooling through the use of twisted film cooling hole. The existing combustor test rig was modified to suit experimental investigations of twisted hole film cooling on a flat plate. The Reynolds number was set at $Re_d = 6200$ to investigate the turbulent flow regime. The computational fluid dynamics (CFD) software was employed for the numerical simulation of the experimental configurations and other geometries of the twisted cooling hole. High mesh density was applied in the flow domain to capture the significant details of the flow induced by the twisted cooling hole. Three different cooling hole shapes of circular, rectangular and twisted rectangular were investigated under a constant temperature boundary condition and variable thermo-physical properties. The CFD processes were verified through various methods. Simulated results were compared to the experimental measurements giving good agreement and therefore the validation was satisfactory. The results showed that the twisted cooling holes provide a better cooling effectiveness compared to the smooth one. It was found that the cooling effectiveness was enhanced at lower blowing ratios by about 1.1-1.5 times than that of a smooth film cooling hole. This effectiveness enhancement was accompanied by an appreciable increase in heat transfer coefficient in the range of 1.2-1.6. The improvement in the thermal performance was also found to be in the range of 1.2-1.5. Eventually, the heat transfer coefficient correlation relevant to the parameter studied in the present work was proposed.

ABSTRAK

Peningkatan suhu salur masuk turbin (TIT) adalah perlu untuk pembaikan kecekapan therma dan keluaran kuasa lebih tinggi untuk enjin turbin gas generasi mendatang. Sejak beberapa dekad yang lalu, pelbagai usaha telah di lakukan untuk meningkatkan TIT menerusi strategi penyejukan bilah yang lebih efektif untuk mengekalkan suhu bilah di bawah takat lebur bahan bilah tersebut. Teknik pendinginan saput telah melalui penyelidikan yang meluas untuk mencapai TIT lebih yang tinggi. Kajian penyelidikan ini telah dijalankan melalui ujikaji dan kaedah berangka, untuk mengkaji satu kaedah baru peningkatan pendinginan saput melalui penggunaan lubang pendinginan saput berpintal. Rig ujian pembakaran sediada telah diubahsuai untuk penyelidikan secara ujikaji pendinginan saput lubang berpintal di atas plat rata. Nombor Reynolds telah ditetapkan pada 6200 untuk mengkaji aliran dalam rejim gelora. Perisian dinamik bendalir berbantu komputer (CFD) digunakan untuk simulasi berangka konfigurasi ujikaji dan geometri-geometri lain lubang pendinginan berpintal. Ketumpatan jejaring simulasi yang tinggi digunakan di dalam domain aliran untuk menangkap butiran aliran penting secara terperinci yang teraruh oleh lubang pendinginan berpintal. Tiga bentuk keratan lubang pendinginan iaitu bulat, empatsegi dan empatsegi berpintal telah diselidik di bawah keadaan suhu malar dan aplikasi sifat pembolehubah thermo fizikal yang lain. Proses simulasi CFD telah melalui penentusahan melalui berbagai kaedah. Keputusan simulasi apabila dibandingkan dengan pengukuran ujikaji menghasilkan perbandingan yang baik dan oleh itu pengesahsahihan adalah memuaskan. Seterusnya, keputusan ujikaji menunjukkan lubang penyejukan berpintal menghasilkan keberkesanan pendinginan yang lebih baik berbanding jenis licin. Didapati juga keberkesanan pendinginan pada nisbah peniupan rendah telah dapat dipertingkatkan sebanyak 1.1-1.5 kali lebih baik dari lubang pendinginan saput licin. Peningkatan keberkesanan ini juga disertai dengan peningkatan ketara pekali pindahan haba sebanyak 1.2-1.6. Peningkatan prestasi haba juga diperolehi diantara julat 1.2-1.5. Seterusnya, sekaitan pekali pindahan haba yang berkaitan dengan parameter yang dikaji dalam kajian ini telah dicadangkan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

C_p - Specific heat, [W/kg.k]
D_j - Hydraulic diameter of film hole, [m]
D_h - Hydraulic diameter of the main duct, [m]
h - Heat transfer coefficient, [W/m^{2}K]
k - Thermal conductivity of plate, [W/m.K]
L - Length of film hole, [m]
Nu - Nusselt number, [-]
P - Pressure, [N/m^2]
p - Film hole pitch, [m]
Pr - Prandtl number[-] ,
q'' - Heat flux per unit area, [W/m^2]
r - Refinement ratio, [-]
Re - Reynolds number, $(\rho ud/\mu)$, [-]
S - Thickness of acrylic plate, [m]
SST - Menter’s shear stress transport turbulence model
T - Temperature, [K]
t - Time, [s]
T_{atm} - Atmospheric temperature, [K]
T_w - Wall temperature, [K]
Tu - Turbulence intensity, [-]
Um - Normal main stream velocity in x-direction, [m/s]
X - Axial distance, [m]

GREEK SYMBOLS

η - Film effectiveness

φ - Overall cooling effectiveness

ε - Turbulent kinetic energy dissipation rate

τ_{ij} - Specific Reynolds stress tensor

τ_j - Time step for Duhamel’s superposition theorem

T_{mj} - Temperature step for Duhamel’s superposition theorem

ν - Kinematic viscosity of the fluid, [m^2/s]

ρ - Density of fluid, [Kg/m^3]

μ - Dynamic viscosity, [$N.s/m^2$]

α - Angle of twisted film cooling hole[°]

$\bar{\alpha}$ - Thermal diffusivity of the cast acrylic

β - Angle of the holes[°]

SUBSCRIPT SCRIPT

h - Hydraulic

in - Inlet

x - Local

$*$ - Dimensionless

LIST OF ABBREVIATIONS

BR - Blowing ratio

DR - Density ratio

GCI - Grid Independence Index

Gz - Graetz number

h_f / h_0 - Heat transfer coefficient

h_f - Heat transfer coefficient with coolant injection

h_0 - Heat transfer coefficient without coolant injection

NHFR - Net heat flux reduction

RTD - Resistance temperature detector

ROI - Region of interest

TIT - Turbine inlet temperature

TIR - Temperature of infrared camera

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1. Background

Cooling techniques play a key role in improving efficiency and power output in modern gas turbines [1]. Film cooling is one of the most effective and widely used cooling methods applied to gas turbine blade to prevent thermal failure in extremely high temperature operations [2].

The temperature of a gas turbine especially the turbine inlet temperature (TIT) is increased year-by-year in order to increase the output power of the turbine, and it has come to a stage that the required TIT is higher than the melting point of the blade material. The blade must be effectively cooled to ensure that the engine works normally [3]. Figure 1.1 shows a turbine blade of a gas turbine engine that uses film cooling technique, where the cooling holes are equally spaced and arranged in rows.

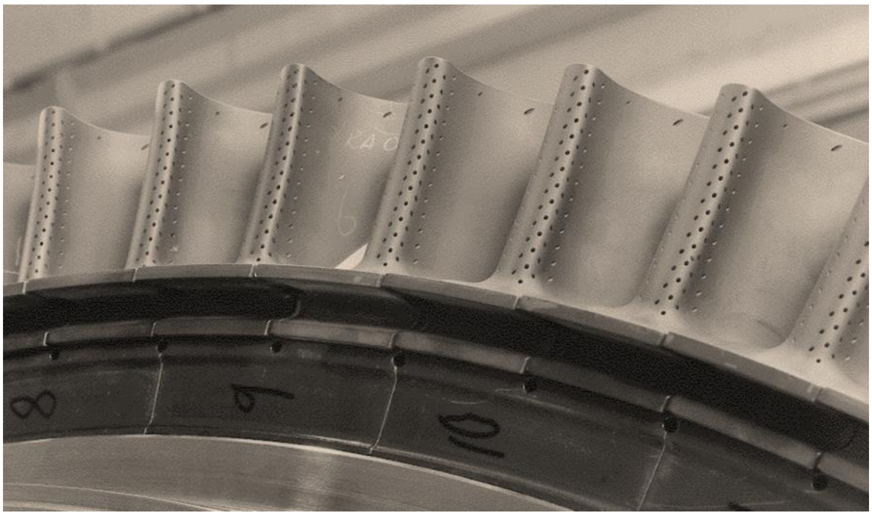

Figure 1.1 Turbine blade

The increased role of gas turbine engines for power generation such as the generation of electrical power and the powering of aircraft flight have generated a lot of interest among researchers leading to advancement in research in turbine cooling technology. Cooling holes shield components from temperatures that are often higher than their melting point, making their precise design and manufacture a critical feature of the engine.

The need for a more efficient thermal power output has also led to the development of more advanced gas turbines thus requiring lower flow rate for the film cooling necessary for keeping the gas turbines working under controlled temperatures [5]. Ghorab [6] carried out several studies and have looked into the complexities associated with the heat and flow processes of gas turbine blade film cooling with the intent of determining the best cooling technique.

Advanced film cooling techniques are vital in the effort to increase cooling performance, thus increasing the gas turbine thermal efficiency. Throughout the last few years, film-cooling strategies have been developed to maintain a blade temperature below the alloy melting point. Cooling hole geometries play a very important role in the enhancement of film cooling over a turbine blade surface.

1.2. Film cooling

To improve the thermal efficiency of a gas turbine, higher TIT is desired requiring more effective cooling strategies of the components downstream. Film cooling of the high pressure turbine is commonly employed in modern turbine designs [7].

The coolant flow is injected from the compressor and is bled through discrete film cooling holes on the surface of the blade. The role of the coolant layer is to protect the components on the high temperature gas path and therefore increases the life of these components. The interaction between the coolant flow and the hot flow causes aerodynamic losses in the turbine stage.

In addition, coolant air represents a loss of the process air available for power or thrust. For these reasons one of the main objectives in cooling design is to use coolant as minimal as possible while ensuring a proper coverage of the coolant on the hot gas path components.

1.3. Dynamics of a jet in a cross flow

Understanding the dynamics of jet in cross flow is crucial in several applications like fuel injection in combustion chambers, thrust vectoring of high speed turbojets and VSTOL (vertical or short take off left) aircrafts, pollutant dispersal from chimneys and film cooling of gas turbines. Figure 1.2 shows a modern turbine with the transition duct and first turbine stage highlighted.

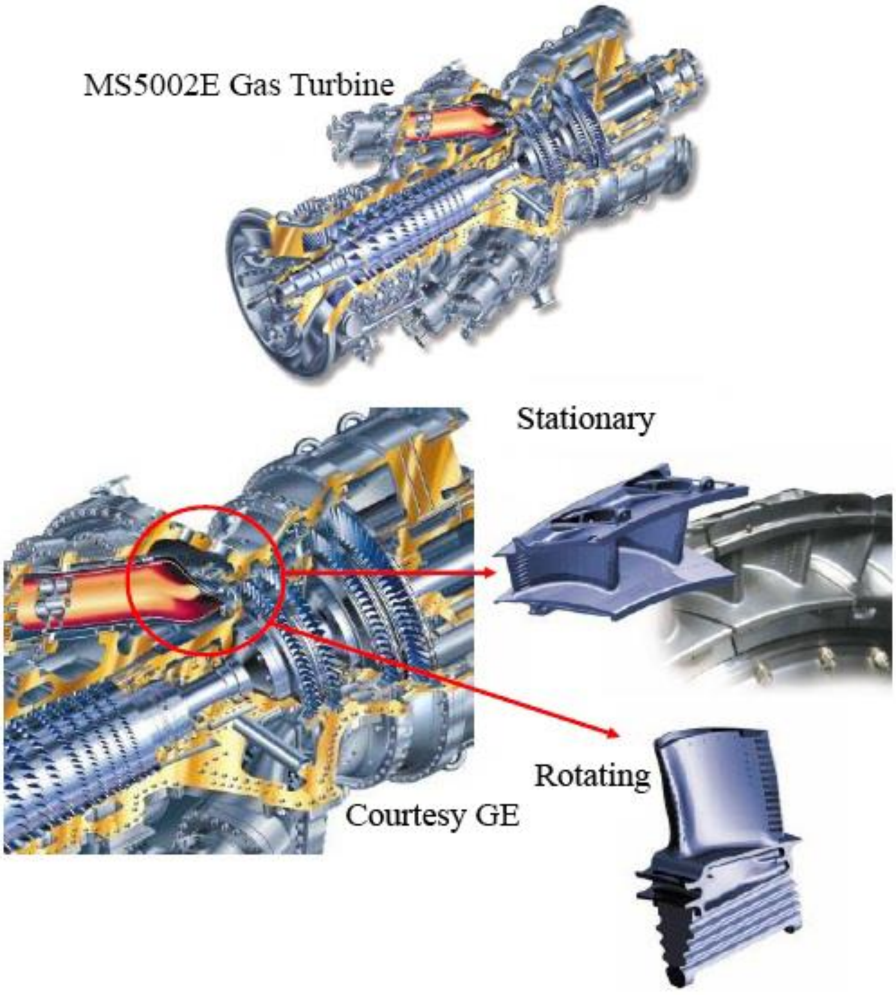

Figure 1.2 MS5002E gas turbine and first stage detail [8].

There have been extensive numerical [9, 10, 11, 12] and experimental [13, 14, 15, 16] studies that have explored the dynamics of jet in cross flow.

1.4. Problem statement

Cylindrical film cooling holes are the most economical to manufacture, but shaped holes have been widely used in military and commercial engines due to the better cooling performance than cylindrical holes [17]. Film cooling has becomes the most common and important cooling techniques in rotor and stator blades of a gas turbine and has been continuously researched. The need for more power output as well as better thermal efficiency in future advanced gas turbine necessitated a higher TIT. Higher TIT will significantly contribute to the increase in power and thermal efficiency. However, the subsequent increases in the turbine blade temperatures need to be cooled effectively and in many instances by a better film cooling technology. High performance and more advance film cooling technologies are needed to protect the surface of the blade and this can be obtained through various innovative methods. Therefore, many new film cooling configurations have been researched by utilizing swirling motion generator to create vortex to the coolant flow, to improve cooling performance. Coolant injection with a suitable swirling motion could lead to a significant improvement in film cooling effectiveness. In this study, the feasibility of employing twisted cooling hole to produce the swirling motion will be investigated to determine the enhancement in cooling effectiveness and the corresponding heat transfer coefficient. The unique twisted hole shape is envisaged to induce vortices near the secondary hole of the coolant flow and these vortices will help to keep the plate surface cold.

1.5. Research Hypothesis

Based on the literature review in Chapter two, advanced film cooling hole geometry are essential for the next generation gas turbine engines. Several studies to enhance the cooling effectiveness and heat transfer coefficient have been considerably carried out. However, there are still many avenues to achieve a better cooling technique.

It hypothesizes that the mixing of flow between main flow (hot) and the injection from twisted cooling holes (cool) will produce a unique film cooling characteristics. The modification to the film cooling characteristics generated by the ensuing vortices could be controlled by the hole twisted angle and the secondary cooling hole angle. This unique flow pattern are studied using advance CFD technique validated by a reliable experimental method and the result could be deduced in term of the heat transfer performance and film cooling effectiveness.

1.6. Research questions

Following the statement of the problem, the research questions for this particular study are as follows:

1- How can the degree of twisted angle of holes affect the cooling effectiveness and the heat transfer coefficient?
2- What is the effect of secondary holes angle (β) on the cooling effectiveness?
3- Does the cross section shape of twisted holes affect the effectiveness and the heat transfer coefficient?
4- What is the mechanism of which the effectiveness being enhanced in twisted holes?
5- Can this mechanism be studied effectively using CFD simulation?

1.7. Objectives

The main goal of this study is to determine the cooling effectiveness enhancement on blade turbine surface due to twisted holes arrangements in order to achieve best cooling effectiveness. This main goal can be achieved by following these objectives.

1. To determine the effect of twisted cooling angles (α) experimentally of holes and the secondary hole cooling angles of the hole (β) (30°, 45° and 90°) on the effectiveness (η) and the heat transfer coefficient (h_f/h_o).

2. To determine the effect of twisted shape of holes (circular, rectangular and hexagonal) numerically on the cooling effectiveness (η) and the heat transfer coefficient (h_f/ho).

1.8. Scope of Work

In order to ensure the success of the research, several scopes have been identified as follows:

1- Turbulent convective heat transfer of Newtonian fluid (air) with all fluid properties such as viscosity μ, heat capacity C_P and thermal conductivity k are assumed to vary with temperature.

2- The same flow temperature will be considered for all cases, i.e. the hot flow will be at T_m=350 K and the cold flow from cooling holes will be at Tj=300 K.
3- The study will be carried out experimentally and numerically.
4- Different blowing ratio (BR) of 0.5 to 2.0 will be used.

The experimental study will be carried out using the existing gas turbine combustion rig with a modified rectangular working section. The same configuration will be meshed and simulated numerically using commercial computation fluid dynamics (CFD) codes, ANSYS FLUENT 14. The simulated results will be validated using the measured experimental results.

1.9. Organization of the thesis

This thesis consists of six chapters. This chapter presents the motivation and objective of the current study.

Chapter two contains the literature review, it shows various techniques used to enhance the cooling effectiveness and heat transfer coefficient of gas turbine blade. This chapter classified into parts, experiment studies and numerical studies. Each study in these parts shows in detail the geometry of cooling hole, limitation and outcomes.

Apparatus and methodology to the test rig is described entirely in chapter three. The test rig has been built to investigate the film cooling effectiveness and heat transfer coefficient performances of different cooling hole geometries on the flat plates. The description of the design, construction, and development of the mechanical, instrumentation, and automated data acquisition systems will be clarified in Chapter three. In addition, this chapter will be closed by a discussion of the uncertainty analyses, experimental procedure.

Chapter four focus on the setting up of the numerical simulation such as the physical domain and the detail of the CFD computational process, as well as the method to ensure reliable outputs.

Through chapter five, the performance film cooling effectiveness of the twisted film cooling hole has been investigated experimentally and numerically. The film cooling performance of the corrugation has been presented and compared with other traditional and advanced published cooling holes geometries (smooth hole). The summary of the adiabatic and conjugate film cooling performance for numerical study will be presented at the end of chapter five.

A conclusion of the current work and recommendation for future studies will be presented in chapter six.

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