EFFECT OF SHAPED HOLES AND DENSITY RATIO ON FILM COOLING EFFECTIVENESS

By

Eng. Hesham Shahat Mohamed Helal

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirement for the Degree of
Master of Science
In

MECHANICAL POWER ENGINEERING

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Prof. Dr. Mahmoud Ahmed Fouad

Mechanical Power Engineering Department
Faculty of Engineering
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2012
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Title of Thesis: “EFFECT OF SHAPED HOLES AND DENSITY RATIO ON FILM COOLING EFFECTIVENESS”
Key Words: Cooling-Shape-Density-Holes-Film Cooling

Summary:

Film cooling is vital to gas turbine blades to protect them from high temperatures. Improvements have been made to the shaping of the cooling hole to provide higher film cooling effectiveness. FLUENT®, computational fluid dynamics software, is used.
Acknowledgment

Firstly, I would like to thank ALLAH, whom I owe everything for his support through all my life.

I would like to thank Prof. Dr. Essam Eldin Khalil Hassan Khalil, Professor of Mechanical Power Engineering, Cairo University and Prof. Dr. Mahmoud Ahmed Fouad Professor of Mechanical Power Engineering, Cairo University, for their deep interest in the subject of this study, their guidance, invaluable discussions in numerous aspects, and their encouragement throughout.

I am grateful to all my friends who supported me. Special thanks go to engineers of Institute of Aviation Engineering and Technology for their support and for giving me the motivation to finish this study.

Finally I owe to my parents, sister and brothers, for their encouragement, emotional support.
Abstract

Film cooling has become a standard method for the protection of the skin of gas turbine blades against the influence high temperatures of the hot gas stream. The cooling air is usually injected into the boundary layer covering the skin through one or two rows of holes. A calculation method to predict heat transfer to the skin of a film cooled wall based on two parameters the film effectiveness and a heat transfer coefficient defined with the adiabatic wall temperature. Improvements have been made to the shaping of the cooling hole to provide higher heat transfer effectiveness. The present work study effect of the four shapes (1) Cylindrical Hole (REF), (2) Cusp Hole(CUSP), (3) Forward – Diffused Hole(FDIFF) and (4) Laterally-Diffused Hole(LDIFF) on film cooling effectiveness on the adiabatic wall flat plate.

The present study of the film cooling to protect from high temperatures through the parametric study of effect of shapes on the hole cooling, blowing ratio and density ratio on the film cooling effectiveness. Stream wise angle (\(\alpha\)) is kept constant at 35 degree and compound (span wise) injection angle (\(\beta\)) is maintained at 90 degree. The series data are collected at fifth blowing ratios (M) = [0.5, 1, 1.25, 1.5 and 2]. The density ratio is constant at 1.97 but it varies from the best shape and blowing ratio at 6, 3, 1.97 and 1.5.

Using computational fluid dynamics software FLUENT ® and choosing the standard k-\(\varepsilon\) model. It was concluded that increasing blowing ratio affected cylindrical holes effectiveness negatively due to the lift-off effect. On the other hand, effectiveness of other holes was much better for higher blowing ratios at certain value and then decreased.
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**List of symbols**

\[ p \] Pressure \( (\text{N/m}^2) \)

\[ D \] Hole diameter (m)

\[ L \] Hole length (m)

\[ M \] Blowing ratio, \[ \frac{\rho_c v_c}{\rho_h v_h} \]

\[ \rho \] Density \( (\text{kg/m}^3) \)

\[ \text{DR} \] Density ratio, \[ \frac{\rho_c}{\rho_h} \]

\[ E \] Total energy of a fluid particle constant

\[ F \] External body forces

\[ \bar{\rho g} \] Gravity body forces

\[ G_b \] Generation of turbulent kinetic energy due to buoyancy

\[ G_k \] Turbulence kinetic energy production

\[ h \] Enthalpy, \( \text{kJ/kg} \)

\[ k \] Turbulent kinetic energy, \( \text{m}^2/\text{s}^2 \)

\[ k_{eff} \] The effective conductivity

\[ k_t \] The turbulent thermal conductivity

\[ P \] Hole spanwise spacing

\[ Pr \] Prandtl number, \[ \text{Pr} = \frac{C_p \mu}{k} \]

\[ Pr_t \] Turbulent Prandtl number

\[ Re \] Reynolds number, \[ \text{Re} = \frac{\rho U L}{\mu} \]

\[ t \] Time, s

\[ Tu \] Turbulence level

\[ u \] Instantaneous velocity component in x direction

\[ v \] Instantaneous velocity component in y direction
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( w )</td>
<td>Instantaneous velocity component in z direction</td>
</tr>
<tr>
<td>( U )</td>
<td>Bulk velocity, m/s</td>
</tr>
<tr>
<td>( U_\tau )</td>
<td>Friction velocity, ( U_\tau = \sqrt{\frac{\tau_w}{\rho}} )</td>
</tr>
<tr>
<td>( Y_j )</td>
<td>Mass fraction of species ( j )</td>
</tr>
<tr>
<td>( y^* )</td>
<td>Dimensionless wall unit</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Streamwise (simple) angle</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Spanwise (compound) angle</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Lateral injection angle</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Forward injection angle, Boundary layer thickness</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Turbulence dissipation rate</td>
</tr>
<tr>
<td>( \eta )</td>
<td>Film-cooling effectiveness</td>
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<tr>
<td>( x, y, z )</td>
<td>Cartesian coordinate components</td>
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<tr>
<td>( \mu_t )</td>
<td>Turbulent viscosity, kg/m.s</td>
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<tr>
<td>( \mu )</td>
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# List of Abbreviations

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<td>AMG</td>
<td>Algebraic Multigrid</td>
</tr>
<tr>
<td>CA</td>
<td>Compound Angle</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CUSP</td>
<td>Cusp-Shape</td>
</tr>
<tr>
<td>CYSA</td>
<td>Cylindrically-Round Simple-Angle</td>
</tr>
<tr>
<td>EDM</td>
<td>Electro-Discharge Machining</td>
</tr>
<tr>
<td>FDIFF</td>
<td>Forward – Diffused Shape</td>
</tr>
<tr>
<td>FDSA</td>
<td>Forward-Diffused Simple-Angle</td>
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<tr>
<td>HTC</td>
<td>Heat Transfer Coefficient</td>
</tr>
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<td>LDIFF</td>
<td>Lateral-Diffused</td>
</tr>
<tr>
<td>LDSA</td>
<td>Laterally-Diffused Simple-Angle</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler Velocimetry</td>
</tr>
<tr>
<td>LIF</td>
<td>Laser-Induced Fluorescence</td>
</tr>
<tr>
<td>LFDSA</td>
<td>Laterally- and Forward-Diffused Simple-Angle</td>
</tr>
<tr>
<td>LFDSA-LL-FF</td>
<td>Laterally- and Forward-Diffused Simple-Angle hole with a lateral diffusion angle of ( LL^\circ ) and a forward diffusion angle of ( FF^\circ )</td>
</tr>
<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
</tr>
<tr>
<td>NHFR</td>
<td>Net Heat Flux Reduction</td>
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<td>Particle Image Velocimetry</td>
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<td>PLIF</td>
<td>Planar Laser-Induced Fluorescence</td>
</tr>
<tr>
<td>REF</td>
<td>Cylindrical Shape</td>
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<tr>
<td>RNG</td>
<td>Renormalization group</td>
</tr>
<tr>
<td>RSM</td>
<td>Reynolds Stress Model</td>
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<tr>
<td>SA</td>
<td>Simple Angle</td>
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<tr>
<td>SIMPLE</td>
<td>Semi-Implicit Method for Pressure-Linked Equations</td>
</tr>
<tr>
<td>SST</td>
<td>Shear Stress Transport</td>
</tr>
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<td>TBC</td>
<td>Thermal barrier coating [K]</td>
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Chapter 1.  INTRODUCTION

1.1 Film Cooling

Over the past fifty years, aircraft and power generation gas turbine designers have endeavored to increase the combustor exit and high-pressure turbine stage inlet temperatures. With higher combustor exit temperatures, improved efficiency and reduced fuel consumption can be achieved. Similarly, in aircraft application, the higher temperatures lead to increased thrust. Unfortunately, these higher temperatures have jeopardized the integrity of the high-pressure turbine components and specifically the turbine blades. Modern turbine stage inlet temperatures exceed the melting point temperatures of turbine blade materials. To combat and avert failure of turbine blades in gas turbine engines resulting from these excessive operating temperatures, film cooling has been incorporated into blade designs. In film cooling, cool air is bled from the compressor stage, ducted to the internal chambers of the turbine blades, and discharged through small holes in the blade walls. This air provides a thin, cool, insulating blanket along the external surface of the turbine blade, as Shown in Figure 1.1.

![Figure 1-1: A Typical Turbine Blade with Film Cooling Holes [1]](image)

Film cooling has become a standard method for the protection of the skin of gas turbine blades against the influence of the hot gas stream. The cooling air is usually injected into the boundary layer covering the skin through one or two rows of holes. A calculation method to predict heat transfer to the skin of a film cooled wall based on two parameters the film effectiveness and a heat transfer coefficient defined with the adiabatic wall temperature has been widely accepted. More recently, those sections of a turbine blade skin requiring intensive cooling are covered over its entire area with holes through which cooling air is ejected. A different method to predict the temperature of this section by this “full coverage film cooling” has been proposed which is based on
two different parameters $\alpha$ and $M$. The air used for the cooling of the perforated section of the skin also provides protection to a solid section located downstream in the normal film cooling process. The two methods are reviewed, and it is discussed under what conditions and in which way results obtained with one method can be transformed to the parameters used in the other one.

1.2 **Turbine Blade Cooling Concepts**

The turbine inlet temperatures of gas turbines have increased considerably over the past years and will continue to do so. This trend has been made possible by the advancement in materials and technology, and the use of advanced turbine blade cooling techniques. The development of new materials as well as cooling schemes has seen the rapid growth of the turbine firing temperature leading to high turbine efficiencies. The blade of the first stage must withstand the most severe combination of temperature, stress, and environment; it is generally the limiting component in the machine. Figure 1.2 shows the trend of firing temperature and blade alloy capability.

![Figure 1-2: Firing temperature increase with blade material improvement [1]](image)

According to Gas Turbine Engineering Handbook [1], from the period from 1950 to 2001, turbine bucket material temperature capability has advanced approximately 472°C, approximately 10°C per year. The importance of this increase can be appreciated by noting that an increase of 56°C in turbine firing temperature can provide a corresponding increase of 8-13% in output and 2-4% improvement in simple-cycle efficiency. Advances in alloys and processing, while expensive and time-consuming, provide significant incentives through increased power density and improved efficiency. The cooling air is bled from the compressor and is directed to the stator, the rotor, and
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other parts of the turbine rotor and casing to provide adequate cooling. The effect of the coolant on the aerodynamics depends on the type of cooling involved, the temperature of the coolant compared to the mainstream temperature, the location and direction of coolant injection, and the amount of coolant. In most literature, a number of these factors are being studied experimentally in annular and two-dimensional cascades. In high temperature gas turbines, cooling systems need to be designed for turbine blades, vanes, end walls, shroud, and other components to meet metal temperature limits. The concepts underlying the following five basic air-cooling schemes are (figure 1.3)

1- Convection cooling
2- Impingement cooling
3- Film cooling
4- Transpiration cooling
5- Water cooling

![Various suggested cooling schemes](image)

**Figure 1-3: Various suggested cooling schemes [1]**

Until the late 1960s, convection cooling was the primary means of cooling gas turbine blades; some film cooling was occasionally employed in critical regions. Film cooling in the 1980s and 1990s was used extensively. In the year 2001, steam cooling is being introduced in the production of frame type engines used in combined cycle applications. The modern turbines have very high pressure ratios and this leads to compressor air leaving at very high temperatures, which affects their cooling capacity.
1.3 Cooling Schemes

1.3.1 Convection Cooling

This form of cooling is achieved by designing the cooling air to flow inside the turbine blade or vane, and remove heat through the walls. Usually, the air flow is radial, making multiple passes through a serpentine passage from the hub to the blade tip. Convection cooling is the most widely used cooling concept in present day turbines. Convection cooling scheme is shown figures 1.4 and 1.5.

Figure 1-4: Convection and impingement cooling [1]
1.3.2 Impingement Cooling

In this high-intensity form of convection cooling, the cooling air is blasted on the inner surface of the blade by high-velocity air jets, permitting an increased amount of heat to be transferred to the cooling air from the metal surface. This cooling method can be restricted to desired sections of the blade to maintain even temperatures over the entire surface. For instance, the leading edge of a blade needs to be cooled more than the mid chord section or trailing edge, so the gas is impinged. Impingement cooling scheme is shown in figure 1.4.

1.3.3 Film Cooling

This type of cooling is achieved by allowing the working air to form an insulating layer between the hot gas stream and the walls of the blade. This film of cooling air protects a blade in the same way combustor liners are protected from hot gases at very high temperatures. Film cooling scheme is shown in figure 1.5.