INVESTIGATION OF FILM COOLING EFFECTIVENESS FROM CYLINDRICAL COOLING HOLE WITH ANTI VORTEX GENERATOR BY NUMERICAL SIMULATION

ABDALLAH ALI ABU.ZARIDA

A project report submitted in partial fulfilment of the requirement for the award of the
Master of Engineering (Mechanical)

Faculty of Mechanical and Manufacturing Engineering
University Tun Hussein Onn Malaysia

JULY 2015

DEDICATION

This project is dedicated to my lovely parents,
Haji Ali Mustafa Abu.zarida and Hajjah Fatima Mohammed Abulim
My brothers and my sisters
And my nieces and nephews
My lecturers and all my friends especially Mohamad AL-melian, Abobaker albishti and
Dr. Salah Alfalah
And my Country Libya
For giving me support and showing faith in me.
Love you always.
I could have never done it without you
I treasure you all
Thank you for all the love, support and encouragement

ACKNOWLEDGMENT

All praise for almighty Allah S.W.T, the most gracious the most merciful and peace by upon our prophet Mohammed along with his family and good friends. I am grateful to Allah S.W.T for giving me help and permission to prepare and accomplish this master project.

I thank all of my brothers and sisters especially my father Ali for supporting me all the time and he still do.

I will not miss the opportunity to thank my supervisor **DR. HAMIDON BIN SALLEH** whose encouragement, support and supervision from the preliminary to the conclusion level enabled and motivated me to accomplish this project.

Many thanks for all of my friends and for everyone helped and prayed from me.

ABSTRACT

This study deals numerical study of the effect of anti vortex generator (AVG) on the film cooling performance of a circular cooling hole which has diameter (*d* = 20 mm) on a flat plate. The interaction between the jet cooling air and mainstream will result kidney vortex which will eliminate the film cooling effectiveness. Two types of AVG with different heights (H = 0.5 *d* and 0.25 *d*) are designed to eliminate the kidney vortex and investigate best film cooling effectiveness, where each of them is mounted to the flat plate upstream of the cooling hole by changing its lateral positions (A = 0.0 *d*, 0.25 *d*, 0.5 *d* and 0.75 *d*) with respect to the hole centerline and for each type has different distance respect to hole centerline. The changing of blowing ratio (BR = 0.5-1.5) was considered in this study. As for the validation, the present study was compared with the previous research done by other researchers using the results obtained from experimental data. The steady turbulence model shear stress transport (SST) that was used to simulate a film cooling configuration. The results have been presented in terms of laterally averaged film cooling comparison graphs, velocity field on x/d = 3.0, non-dimensional temperature on x/d = 3.0 and the vorticity on x/d = 3.0 which explained how the results obtained. Cases 04 and 07 gave the best positions for AVG where case 04 gave wide covered for laterally average film cooling effectiveness ($\eta = 0.35$), while case 07 gave the highest expand distribution and the maximum value for film cooling effectiveness ($\eta = 0.66$).

ABSTRAK

Kajian ini membincangkan kajian berangka kesan penjana anti vorteks (AVG) kepada prestasi filem penyejukan lubang bulat yang mempunyai diameter (d = 20 mm) di atas pinggan rata. Interaksi antara jet penyejukan udara dan slirsn utama akan mengakibatkan *kidney vortex* yang akan menghilangkan keberkesanan filem penyejukan tersebut. Dua jenis AVG dengan ketinggian yang berbeza (H = 0.5 d dan 0.25 d) direka untuk menghapuskan *kidney vortex* dan menyiasat keberkesanan filem penyejukkan, di mana setiap daripadanya dipasang aliran atas plat rata lubang penyejukan dengan menukar kedudukan lateral (A = 0.0 d, 0.25 d, 0.5 d dan 0.75 d) berkenaan terhadap garisan tengah lubang dan bagi setiap jenis perbezaan jarak berkenaan terhadap garisan lubang tengah. Perubahan nisbah tiupan (BR = 0,5-1,5) telah dipertimbangkan dalam kajian ini. Sebagai pengesahan kajian, kajian ini telah dibandingkan dengan kajian terdahulu oleh penyelidik yang menggunakan keputusan yang diperolehi daripada data eksperimen. *Steady Turbulence Model Shear Stress Transport* (SST) telah digunakan untuk mensimulasikan konfigurasi filem penyejukan. Keputusan telah dibentangkan dari segi sisi purata graf filem penyejukan perbandingan, medan halaju pada x / d = 3.0, suhu tanpa dimensi pada x / d = 3.0 dan pusaran pada x / d = 3.0 yang menjelaskan bagaimana keputusan yang diperolehi. Kes 04 dan 07 memberikan kedudukan yang terbaik terhadap AVG di mana kes 04 memberi pelindungan menyeluruh terhadap purata keberkaesanan filem penyejukan($\eta = 0.35$), manakala Kes 07 memberi taburan pengembangan yang tertinggi dan nilai maksimum untuk keberkesanan filem penyejukkan ($\eta = 0.66$).

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOL AND ABBREVIATIONS

W_{net} - Net work [W]
Q_{in} - Heat supplied [W]
TIT - Turbine inlet temperature
AVG - Anti vortex generator
DR - Density ratio
BR Blowing ratio
SST - Shear stress transport
CRVP - Counter rotating vortex pair
T_∞ - Mainstream temperature [K]
T_c - Coolant temperature [K]
T_{aw} - Adiabatic wall temperature [K]
η - Film effectiveness
ρ_c - Cool air density [kg/m^3]
ρ_∞ - Mainstream air density [kg/m^3]
U_c - cool air velocity [m/s]
U_∞ - mainstream air velocity [m/s]
CFD - Computational Fluid Dynamics
l/d - Hole length to diameter ratio
d - Hole diameter [mm]
p - Hole pitch [mm]
H - Height of AVG [mm]
A - Off-set distance [mm]
P - Pressure [Pa]

Ω_u - Mainstream turbulence intensity

Ω_c - Coolant jet turbulence intensity

Re - Coolant Reynolds number

θ - Non-dimensional temperature

T_f - local fluid temperature

T_∞ - Mainstream temperature [K]

T_1 - Compresor inlet air temperature [K]

T_2 - Combustion chamber inlet temperature [K]

T_3 - Turbine hot gases inlet temperature [K]

T_4 - Turbine exhaust gases temperature [K]

x/d - Distance x to diameter ratio

RAE - Relative absolute error

(U/U_∞) - Velocity ratio

LIST OF APPENDIXES

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this chapter, the main idea of gas turbine and film-cooling technologies will be discussed. Some attention will be paid to existing experimental researches in order to obtain reliable results in the future.

1.2 Background

The interest to gas turbine appeared approximately a century and half ago, but the real success was achieved in 1930, when Frank Whittle got a patent award on the jet engine and made his static test of it in 1937. Two years later, a jet-engine- powered flight was demonstrated by Hans von Ohain. Gas turbines are successfully used by the aircrafts and the stationary power plants nowadays. Back in 1939, the combustion turbine (gas turbine) was used for generating electricity but today it becomes one of the most widely-used power generating technologies (Yunus Cengel and Micheal Boles, 2007). Usually, they operate as in open cycle as shown in Figure 1.1 below.

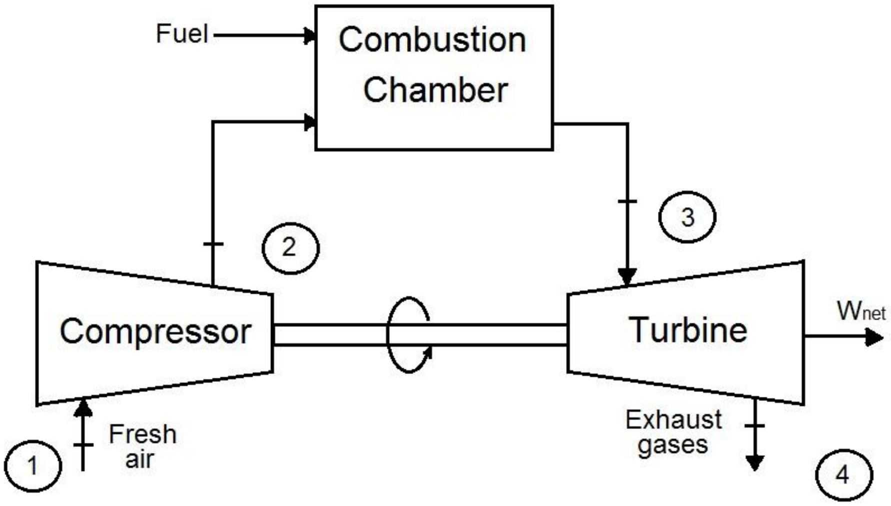

Figure 1.1: An open-cycle gas-turbine engine

1.2.1 Gas turbine operation

The fresh air comes to the compressor where temperature and pressure increase. The high pressure air flows into the combustion chamber where the fuel injected is burned with constant pressure. On the next stage, the high-temperature gases enter the turbine where they expand to the atmospheric pressure producing the power. After this, the exhaust gases leave the turbine to the ambient air.

But the main idea for gas turbine is depending on the close cycle, what uses the ideal Brayton cycle or Joule cycle. In this cycle, the stages are equal to open cycle but there are differences in the combustion and exhaust processes. The first changes to the constant pressure heat addition process and the second to the constant pressure heat rejection process to the ambient air.

There are four reversible processes in the Brayton's cycle (Figure 1.2):

- Isentropic compression(in a compressor)
- Constant-pressure heat addition
- Isentropic expansion (in a turbines)
- Constant-pressure heat rejection

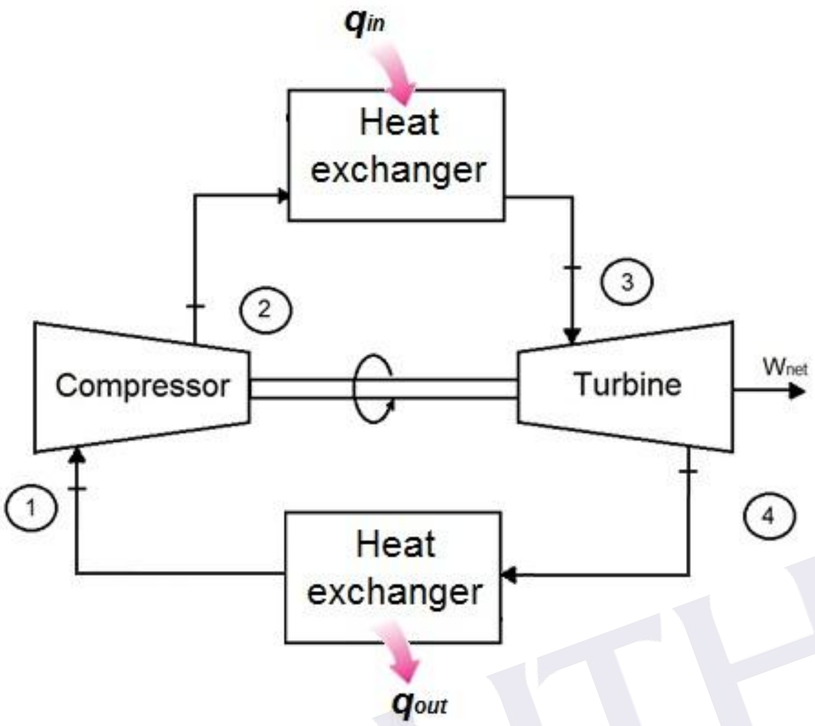

Figure1.2: A closed-cycle gas-turbine engine

To improve gas-turbine efficiency, the turbine inlet temperature must be increased. Thus, such increase could be possible by the development of new materials and creation of cooling techniques.

The Brayton's cycle can be performed by temperature–entropy diagram (Figure 1.3). The cycle consists of an isentropic compression of the gas from state 1 to state 2; a constant pressure heat addition to state 3; an isentropic expansion to state 4; and an isobaric closure of the cycle back to the initial state. (Yunus Cengel and Micheal Boles, 2007)

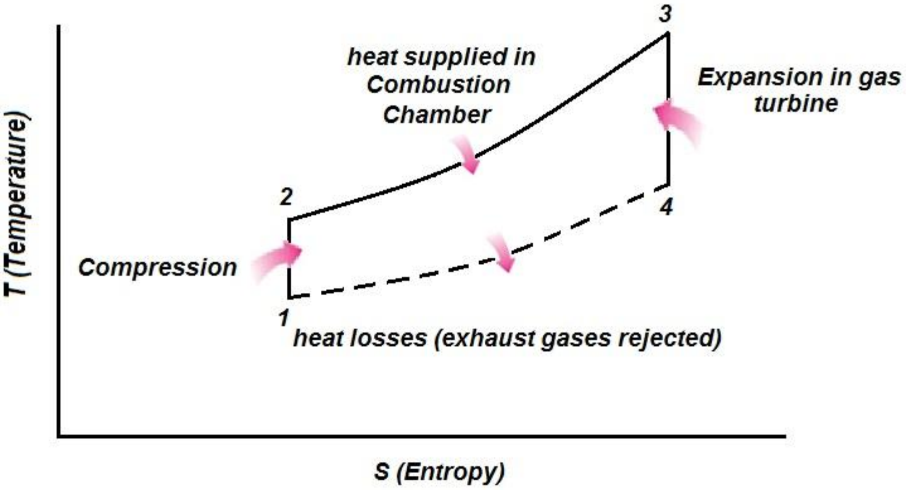

Figure 1.3: Temperature–Entropy Plot of Ideal Brayton Cycle

The industrial gas turbine structure is demonstrated on the Figure 1.4. It consists of compressor, combustor and turbine. After incoming air is compressed in the compressor, it supplied to the combustor. There high pressure air is mixed with the fuel and burned. The results of the combustion are the high pressure, temperature and velocity gas. The object of the turbine is extracting the energy from the gas.

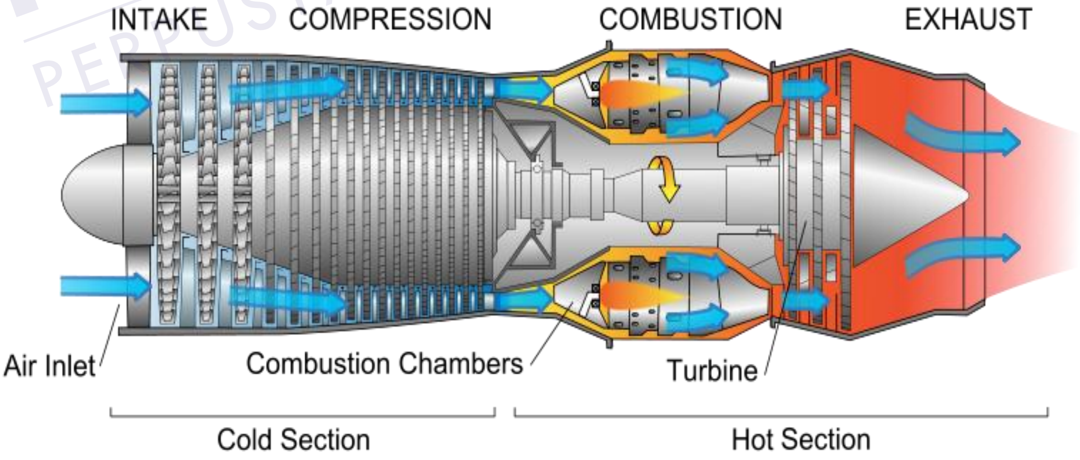

Figure 1.4: Industrial Gas Turbine (www.article4ever.wordpress.com)

The thermal efficiency of the Brayton's cycle can be presented by equation below, where W_{net} , Q_{in} ,T_3, and T_4 are the net work produce by the cycle [W], the heat supplied to the cycle [W], inlet temperature of the turbine [K], and the exit temperature of the turbine [K], respectively. The higher turbine inlet temperatures produce higher overall thermal efficiency of the cycle. (Yunus Cengel and Micheal Boles, 2007)

$$\eta_{th,Brayton} = \frac{W_{nett}}{q_{in}} = 1 - \frac{T_4}{T_3} \tag{1.1}$$

This formula can be written as follow:

$$\eta_{th,Brayton} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_{pg} * (T_3 - T_2)}{C_{pg} * (T_4 - T_1)} \tag{1.2}$$

So, last formula will become as follow:

$$\eta_{th,Brayton} = 1 - \frac{(T_3 - T_2)}{(T_4 - T_1)} \tag{1.3}$$

1.2.2 Turbine cooling

The increasing demand for better performance gas turbine provokes the turbine inlet temperature rising. Nowadays, the gas turbines work at the temperature range around 1800K- 2000K, what is much higher than the melting temperature of the turbine components materials. Such increasing of the turbine inlet temperature became possible because of application of cooling scheme on the turbine components. Film cooling is the injection of cold air to provide a layer of cool fluid between the hot gases and the blade surface, reducing heat transfer to the surface.

Actually, gas turbine blades can be cooled by internally and externally. Internal cooling can be done by the coolant pass through several enhanced serpentine passages inside blades and the heat from the surface will be extracted. Examples of internal cooling method are jet impingement and pin-fin cooling. On the contrary, film cooling is belongs to external cooling. The cool air is being ejected through the film cooling holes, and from a layer of coolant film that protects the wall surface of turbine blades from hot gases. This technique helps to avoid the hot gases directly contact with turbine blades, which will cause damage if the direct contact happens.

Figure 1.5 shows how the film cooling works on turbine blades. Cool air is drawn from compressor and being injected through the inlet of film cooling hole onto the blade surface to protect it from contact with hot gas. The direction of the blade rotation must be opposite with direction of mainstream (hot gas) and the film cooling layer while the film cooling effect can be perform.

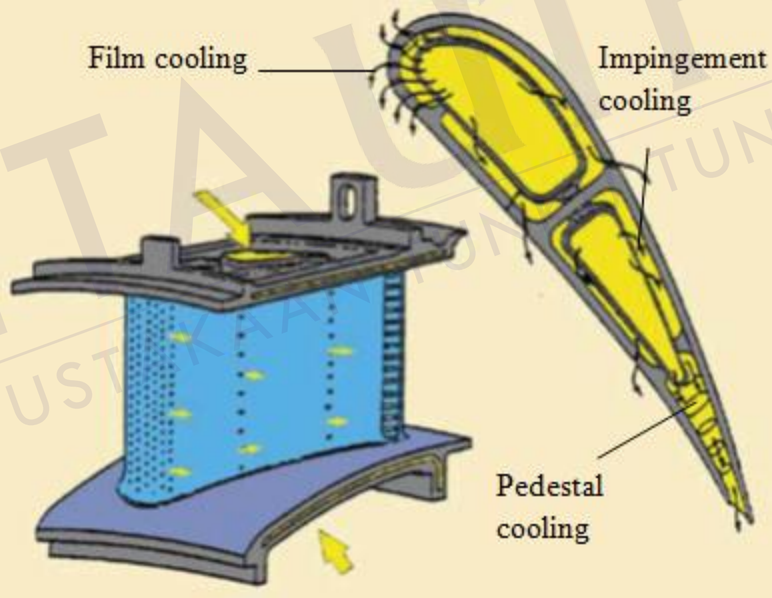

Figure 1.5: Film cooling on a turbine blade (Bogard, 2006)

1.3 Problem statement

Thermal efficiency of a gas turbine can be unswervingly improved by means of higher turbine inlet temperature (TIT). Most of the modern gas turbines are now operating with high (TIT) in the range of 1800K to 2000K, which far surpasses the melting temperature of the turbine components material. Sophisticated cooling scheme is required to help protecting the turbine components from thermal failure.

This high temperature will exceed the thermal limits of the gas turbine components and these high temperatures also will reduce this components lifespan

But the main problem that needs to find solution for it is, jet and main stream interaction made complicated vortex as kidney vortices, i.e. a pair of counter rotating vortices. This vortex will eliminate to investigate high performance for film cooling effectiveness.

1.4 Objectives of study

The objectives of this study are:

1. To generate a counter vortex in order to eliminate the counter rotating vortex pair (CRVP) by using an anti vortex generator (AVG).
2. To determine the best positions for (AVG) to investigate the high performance of film cooling effectiveness.

1.5 Scope of Study

The scopes of this study are:

i. ANSYS CFX Workbench 15.0 for computational fluid dynamics.
ii. The testing inclination angle for cylindrical hole is 35^o.
iii. The data of the simulations depends on the experimental data that is already available. It consists the on the mainstream velocity and temperature also density ratio (DR).

iv. The blowing ratios being tested at M = 0.5, 1.0 and 1.5.
v. The turbulence model that used is shear stress transport (SST).
vi. Using 2 types of an anti vortex generator (AVG) with different laterally positions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The demand of engines with a higher output to satisfy the needs of today has created a challenge to engineers to come up with ways to improve the efficiency of engines. To make this happen, higher turbine inlet temperature (TIT) is needed. However, higher TIT increases thermal load to its hot section components, damaging turbine blades and reducing their life span. Therefore, a cooling technology such as film cooling is required especially for high pressure turbine blades. There are many parameters that may influence on the film cooling performance including inclination angle and the shape of inclination hole, velocity ratio, blowing ratio, pressure ratio, temperature ratio, density ratio, momentum ratio and turbulence intensity.

REFERENCES

A. Azzi and B. a. Jubran, “Numerical modelling of film cooling from converging slot-hole,” Heat Mass Transf., vol. 43, no. 4, pp. 381–388, Mar. 2006.

A. Bradley, “CFD Simulations for Film Cooling Reduced Models at Engine Like Conditions,” no. 1593, (2013).

A. H. and M. E. C. Christian Heneka, Achmed Schulz, Hans-Jörg Bauer. Film Cooling Performance of Sharp Edged Diffuser Holes With Lateral Inclination,” ASME, vol. 134(4), 04, no. 4, p. 8 pages, 2012.

Andreopoulous ,J. and Rodi, W., 1984 Experimental Investigation of Jets in Crossflow Journal of Fluid Mechanics, Vol 138, pp 93-127

B.A. haven and M. Kurosaka., Improved Jet Coverage Through Vortex Cancellation ,AIAA Journal, Vol. 34, No. 11

Barigozzi, G., Franchini, G., and Perdichizzi, A., 2007, “The Effect of An Upstream Ramp on Cylindrical and Fan-Shaped Hole Film Cooling—Part 2: Adiabatic Effectiveness Results,” ASME Paper No. GT2007-27079.

Barigozzi, G., Franchini, G., and Perdichizzi, A., 2007. “The Effect of an Upstream Ramp on Cylindrical and Fan-Shaped Hole Film Cooling—Part 1: Aerodynamic Results,” ASME Paper No. GT2007-27077.

Bogard, David G. "Airfoil film cooling." The Gas Turbine Handbook (2006).

C. H. N. Yuen and R. F. Martinez-Botas, “Film cooling characteristics of a single round hole at various streamwise angles in a crossflow: Part I effectiveness,” *Int. J. Heat Mass Transf.*, vol. 46, no. 2, pp. 221–235, Jan. 2003.

C. Saumweber, A. Schulz, Effect of Geometry Variations on the Cooling Performance of Fan Shaped Cooling Holes, ASME Turbo Expo, Berlin, 2008. GT2008-51038.

C. Saumweber, A. Schulz, S. Wittig, Free-stream turbulence effects on film cooling with shaped holes, ASME J. Turbomach. 125 (2003) 65–73.

Goldstein, R.j., (1971).Film Cooling, In Advance in Heat Transfer. Academic Press, Inc.

H. Kawabata, K.-I. Funazaki, R. Nakata, and D. Takahashi, "Experimental and Numerical Investigations of Effects of Flow Control Devices Upon Flat-Plate Film Cooling Performance.," J. Turbomach., vol. 136, no. 6, pp. 0610211–6102111, Jun. 2014.

Haven ,B.A., Yamagata, D. K., Kurosaka ,M., Yamawaki, S., Maya,T., 1997, "Anti kidney Pair of Vortices in Shaped Holes and their Influence on Film Cooling Effectiveness" ASME Paper 97-GT-45

https://www.article4ever.wordpress.com/2010/04/04/gas-turbine-blade-metallurgy-and fabrication/

Ligrani, P. M., Wigle, J. M., and Jackson, S.W., " Film-cooling From Holes with Compound Angle Orientations: Part 2- Results Downstream of a Single Row of Holes with 6d Spanwise Spacing," ASME Journal of Heat Transfer, Vol. 116, No. 2, 1994, pp. 353-362.

Ligrani, P. M., Wigle, J. M., Ciriello, S., and Jackson, S.W., " Film-cooling From Holes with Compound Angle Orientations: Part 1- Results Downstream of Two Staggered Rows of Holes with 3d Spanwise Spacing," ASME Journal of Heat Transfer, Vol. 116, No. 2, 1994, pp. 341-352.

Lu, Y., Faucheaux, D., and Ekkad, S.V., 2005, "Film Cooling Measurements for Novel Hole Configurations," ASME Summer Heat Transfer Conference, July 2005, Paper No. HT2005-72396

M. Gritsch, A. Schulz, S. Wittig, Adiabatic wall effectiveness measurements of film cooling holes with expanded exits, ASME J. Turbomach. 120 (1998) 549–556.

N. M. Yusop, a. H. Ali, and M. Z. Abdullah, "Computational study of a new scheme for a film-cooling hole on convex surface of turbine blades," Int. Commun. Heat Mass Transf., vol. 43, pp. 90–99, Apr. 2013.

Na, S., and Shih, T., 2007. "Increasing Adiabatic Film-Cooling Effectiveness by Using an Upstream Ramp," ASME J. Heat Transfer, 129, pp. 464–471.

Sargison, J. E., Guo, S. M., Oldfield, M. L.G., Lock, G. D., and Rawlinson, A. J., 2002,“Flow Visualization of a Converging Slot-Hole Film Cooling Geometry,” ASME Paper GT 2002-30177.

Sen, B., Schmidt, D.L., and Bogard, D. G., “Film Cooling with Compound Angle Holes: Heat Transfer,” ASME Journal of Turbo machinery, Vol. 118, No. 4, 1996, pp. 801 807.

Y. Yao, J. Zhang, and Y. Yang, “Numerical study on film cooling mechanism and characteristics of cylindrical holes with branched jet injections,” Propuls. Power Res., vol. 2, no. 1, pp. 30–37, Mar. 2013