Evaluate the effectiveness of cylindrical cooling holes embedded in arc trench over flat plate surface using infra-red technology

Wisam A Ajlan¹, Harbi A Daud² and Nabil J Yasin¹*

¹Enineering Technical College-Baghdad, Middle Technical University, Baghdad, Iraq
²Institute of Technology -Baghdad, Middle Technical University, Baghdad Iraq
E-mail: NabilYasin@toc.edu.iq

Abstract. The present study employed Intra-Red Technology (IRT) to show and measure flat plate surface temperature. Experimental investigation of film cooling holes was achieved. The effect of blowing ratio for the Perspex flat plate samples was obtained using Thermal Image camera and Thermal Wind Tunnel (TWT). A flat plate with (240 mm long x 8 mm height x 120 mm width) was fabricated using the CNC machine. Namely, 9 film cooling holes (4 mm diameter) are placed as one row at a lateral spacing of pitch equal to three times of hole diameter with 35° angle of injection. Intra-Red Technology (IRT) was used to examine the ejected cooling air experimentally through increasing injection BR (BR=0.5, 1 and 1.5). So far, in terms of film cooling performance, the experimental result illustrates noticeable improvement achieved at BR=1 due to a reduction in plate surface temperature. Thermocouple technology was also used in this study by embedding 8 thermocouples in the flat place surface to measure the temperature of the coolant in the midline along the surface. The transient temperature along plate was measured for each BR during the first 500 sec of the test. Consequently, the lower the blowing ratio, the more stable increment in temperature points (gradually increasing) with longer testing time to reach steady state after 1500 sec. Moreover, the cylindrical holes model provides better film cooling efficiency at BR=1 and the arc trench model gave the best enhancement ineffectiveness at BR=0.5 and 1. It was found that, the experimental results were in excellent matching with previous published results. Finally, IRT shows successfully the qualitative temperature distribution on the plate surface.

1. Introduction

Gas turbine blade degradation increases via exposing blades surface to the incoming hot gas and this usually gives rise in thermal stresses of blade components in modern aerospace and power generation applications. Consequently, film-cooling holes technology is efficient way to protract the blades surface by provides the first and best line of defines to overcoming hot gas through, extreme of heat fluxes on the blade surface generated via high temperature [1]. Numerous prior studies detected aerodynamics, heat transfer through examining the film cooling effectiveness. Yuen and Martinez-Botas [2, 3] investigated one row of cylindrical holes over the flat plate surface experimentally. The hole geometry (cylindrical and shaped hole) has considerable effect on exit coolant jet momentum to obtain better film cooling [4]. Many researchers conducted comprehensive survey on the performance of film cooling [5]. Hence, related to the present work for cylindrical holes using IR thermography, numbers of published papers were reviewed. Lu et al. and Lu [4, 6] performed a row of holes embedded in transverse slot. So, different trench depth was observed with two-trench width. The secondary flow was injected at 0.5, 1, 1.5 and 2. 1-D semi-infinite transient heat conduction equation was utilized to evaluate heat transfer coefficient and film effectiveness. Takeishi et al. [7] Employed
low speed wind tunnel to study experimentally the film holes efficiency on a flat plate surface. Different holes shapes were used to examine the influence of swirling coolant flow. Both pressure sensitive paint and particle image velocimetry methods were used in their research. They found that, cooling efficiency improved because of the swirling effects, the interaction between coolant jets and mainstream. Great deals of effort were devoted to enhance cooling holes effectiveness. Recently, Sridharan et al [8] performed film-cooling performance of set assembled tripod holes design. Heat transfer coefficient and film cooling effectiveness on flat plate was evaluated using IR thermography for standard and shaped cylindrical exits with and without tripod holes geometry. The results indicated that tripod holes geometries provide higher effectiveness compared with cylindrical holes and slightly higher cooling performance than shaped holes and about 50% of Coolant air was consumed at BR=0.5, 1 and 1.5. There are two systems of infrared: scanning and staring. In scanning system, heating measured from one point to another. Whereas in staring system, heating measured using x-ray sensor arrays [9]. Lin et al [10] assessed the performance of cylindrical film cooling holes numerically and experimentally using inclined ribs on secondary flow structure. The coolant gas was injected at BR=0.5, 1 and 2 for each case, including two ribbed cross-flow channel (135° and 45°) and plenum case. Transient liquid crystal technique was utilized to measure the coefficient of heat transfer on flat plate and film cooling effectiveness. Moreover, the steady RANS simulation with K-epsilon turbulent model was performed to enhance wall treatment. 1-D semi–infinite unsteady equation is used to reinforce the illustrated results; at BR=1 the film cooling effectiveness for 135° and 45° rib angles have been provided higher value about 38% and 107% compared with plenum case respectively. At 45° rib angles provides about 3.4% higher heat transfer coefficient compared with 135° rib angles. The purpose of this paper is to study the influence of varying the blowing ratio practically with an angle of jet flow 35° for flat plate surface using infrared IR technology and thermal wind tunnel. The experimental test and the analysis time were reduced 3 times compared to a traditional test. However, the infrared system is less using than thermal liquid crystal technique (LCT) and thermal paint technique (TPT) in experimental to study film cooling holes efficiency. This is due to that the infrared system is quite expensive.

2. Flat plate geometry model
The layout of the film cooling holes along streamwise direction is shown in Figure (1). The flat plate specimen was analyzed experimentally using thermal image camera. The main parameters investigated in the current study were holes diameter (4mm), number of holes in a single row (9 holes) and angles of injection (35°).

On flat plate specimen, eight access holes were formed to embedded K-type thermocouples placed in the midline of the specimen and pitch spacing equal to 5*D after the location of the cooling holes. The arc trench was width 10 mm with depth 2mm to keep the coolant air injected smoothly.

Figure 1. Geometry of cooling holes along streamwise direction a) cylindrical hole, b) arc trench.
3. Experimental setup

The incoming mainstream (hot gas) and the secondary coolant have been accomplished via experimental thermal wind tunnel. Figure (2) shows schematic experimental test rig and test model with plenum coolant channel. In all the experimental tests the incoming air was supplied by centrifugal blower. The compressed air directly forwarded to an 18 kW heating system (two group of mesh heater) in the stabilizing section.

![Figure 2. Schematic diagram of experimental set-up with complementary measurement devices.](image)

Three phase controlling system was used to achieve freestream at temperature about 70 °C and the hot air was regulated to the constant mass flow rate via a gate valve to satisfy suitable blowing ratio(BR=0.5 ,1 and 1.5). Therefore, the freestream forced to the test section which is Aluminum rectangular duct with 120 mm in height and 50 mm in width. There was a digital hot wire anemometer fixed at freestream channel located before the test section to measure the hot air velocity. Figure (3) illustrates thermal wind tunnel device set up and experimental arrangement. A solid Perspex plate dimension was (240mm*120mm*8mm) in Cartesian coordinates. Consequently, the solid plate surface temperature was measured by thermal image camera (IR). In addition to, 8 thermocouples (type k) inserted in centerline of test plate to measure the temperature during the test time using Pico USB TC-08. Two cases were fabricated in this study as 9 film cooling holes; a cylindrical holes shape design and cylindrical holes embedded in arc trench over flat plate to evaluate the effectives at different blowing ratio. Figure (4) shows flat plate tested model.

In this study, the secondary flow (coolant) was supplied at temperature about 20 °C from cooling system unit to plenum and to cooling holes. A digital hot wire anemometer also used to measure coolant velocity, which is controlled by valve.

![Figure 3. Thermal wind tunnel device setup.](image)
4. Experimental uncertainty
The uncertainties of the measurement should be undertaken in order to conduct experimental test perfectly and measure film cooling efficiency. The hot wire potable anemometer provides fast and accurate readings with range about \((u=0 \text{ m/sec to } u=30 \text{ m/sec})\) and accuracy of anemometer is ±3 %. In addition to, the accuracy of measurements device which used to measure the wall surface temperatures was ± 1°C for Pico USB TC-08 temperature data logger and ±2 °C thermal image camera. Therefore, the relative film cooling effectiveness uncertainty was about 5%.

5. Operating conditions and procedure
A continuous flow was conducted in thermal wind tunnel using blower. The corresponding main flow velocity, \(R_{eh}\) at the test section is keep at \((1.48, 0.74 \text{ and } 0.49) \times 10^5\) with three blowing ratio BR (0.5, 1 and 1.5) respectively. The secondary flow was injected by cooling system supplier at constant velocity, \(R_{ec}=0.35 \times 10^5\).

Typically, a sequence of steps is required to achieve the measurements. Firstly, the velocities of incoming flow based on BR (0.5, 1 and 1.5) as well as the secondary flow at room temperature (23°C) is dominated. Secondly, two groups of heaters were operates to increase the incoming air temperature from 23 to 70 °C and keep it at 70°C by electrical control system. Continually, eight thermocouples started to measure the temperature with time via Pico USB TC-08 temperature data logger during testing period.

The cooling system was also operates to injected the coolant air through plenum of film holes as a secondary flow at temperature 20 °C. All experimental test were achieved during 1500 second to satisfy steady state flow to capture the distribution of surface temperature using thermal image camera. Figure (5) illustrates instruments which used to measure the temperature, flow velocity and thermal image camera.

![Figure 4](image1.png)

**Figure 4.** Flat plate tested model a) cylindrical holes b) cylindrical holes with arc trench.

![Figure 5](image2.png)

**Figure 5.** Measuring instrument, a) Pico USB TC-08 temperature data logger b) The hot wire potable anemometer c) IR thermal camera.
6. Experimental results analysis

The evaluation of the current experimental approach is accomplished for two tested models. First case model and second model were a cylindrical film cooling holes and cylindrical holes with arc trench respectively. Hence, eight points are located at the mid-span of flat plate surface recording the temperature during 1500 seconds for three different blowing ratios.

Figure (6) and figure (7) illustrates variation of temperature with time. From these figures, it can be seen that the transient temperature was increased gradually from room temperature to $40^\circ$C during the first 500 seconds. The temperatures kept increased during the second 500 seconds until it reached $50^\circ$C. Whereas, it plateau about $55^\circ$C in the last 500 seconds.

![Graph of temperature vs time for cylindrical holes model](image)

**Figure 6.** Stream wise transient temperature located at the mid area of flat plate surface for cylindrical holes model, a) first 500 second and b) third 500 second.
Figure 7. Stream wise transient temperature located at the mid area of flat plate surface for cylindrical holes with arc trench model for BR = 1, a) first 500 second and b) third 500 second.

Figure 8. Stream wise transient temperature with different BR for a) cylindrical holes and b) arc trench model.

As shown in figure (8), the effects of blowing ratio (BR=0.5, 1 and 1.5) for two experimental tested model during the first 500 second. It can be seen that the transient temperature was raised steadily from room temperature and the lower thermocouple temperature was obtained for BR=1. Certainly, due to the coolant air provides better air blanket over flat plat surface at x=40 mm. Moreover, at x=60 mm the cold air also performed good surface protection from the incoming hot air direction.

Figure (9) demonstrates the variation of local film cooling effectiveness through study effect of increasing BR (0.5, 1 and 1.5) for cylindrical holes model. It can be seen that the effectiveness value all must stable at x/d<11 for all blowing ratio. Clearly, the efficiency was improved with the increasing BR from 0.5 to 1. While, the film effectiveness was fluctuated with increased BR from 1 to 1.5 due to mixing flow between hot and coolant air (k type thermocouple tip was embedded to measure plate surface and free stream flow temperature). Hence, more protection occurs at BR=1.

Film efficiency (\( \eta \)) is a function of mainstream temperature (\( T_\infty \)), adiabatic surface temperature (\( T_w \)) and coolant air (\( T_c \)), calculated by using the following equation:
Figure 9. Local film cooling effectiveness over flat plate surface with different BR for cylindrical holes model.

Local film cooling effectiveness data for cylindrical holes with arc trench model were set together with that of base line model i.e. for BR (1 and 1.5) see figure (10). Good enhancement was occurred in effectiveness with arc trench model especially at x/d > 31 for BR=1. Due to the mixing process between primary and secondary air in the arc trench so good surface protection was obtained. Whereas, the fluctuation in film cooling data was acquired at BR=1.5 compared with cylindrical holes model.

Figure 10. Local film cooling effectiveness for cylindrical holes and arc trench model at a) BR=1 and b) BR=1.5.
In this paper, IR thermal image camera (FLIR) was selected to capture flat plate surface temperature with different blowing ratio for cylindrical model and arc trench model. Hence, plate surface image was taken after 1500 second of the testing time. Figure (11 a) shows the lower surface temperature pattern occurred at BR=1 due to wide range of low spectrum surface temperature appears downstream of the cylindrical holes compared with BR=0.5 and 1.5. Figure (11b) illustrates surface temperature image for arc trench model. It was clear that in all images pattern showed the hot air and coolant air mixed inside the arc trench and forward over plate surface. Consequently, good reduction in surface temperature pattern for BR =0.5 and 1 compared with BR =1.5.

IR image was also analyzed using FLIR data program to fined flat plate surface temperature data. So, figure (12 a) and figure (12 b) shows local film cooling effectiveness surface with different blowing ratio for cylindrical model and arc trench model. It can be seen that good matching in film cooling obtained at x/d< 5. Moreover, the effectiveness was enhanced at BR=1 for both models while it was reduced for BR=1.5 due to the coolant air penetration.

The effect of cylindrical holes model and arc trench model on film cooling effectiveness also detected in figure (13 a) and figure (13 b) for BR=0.5 and 1. New model (arc trench) accomplished more improvements in effectiveness for both blowing ratio due to diffusivity of mixing flow over flat plate.
Figure 13. Film cooling effectiveness using IR thermal image data. for cylindrical holes model and arc trench model at a) BR=0.5 and b) BR=1.

Figure 14. Comparison of experimental result of film cooling effectiveness with previous results from [11-13].

Figure (14) shows an excellent matching between experimental results and data obtained from previous studies. Film cooling effectiveness obtained from IR data for cylindrical holes model with angle of injection $35^\circ$ compared previous published paper and good matching with Sinha et.al [11] and Kohli et al [12]. While small deviation occurred near the holes region with Li et al [13] because of different ratios of length-to-diameter were studied in their study.

7. Conclusions
IR thermal image camera has been presented clearly flat plate surface temperature pattern. In addition to confirm experimentally the effect of increasing blowing ratio with baseline film cooling model and arc trench model.

(1) Good enhancement is occurred in film cooling effectiveness for baseline model and additional improvement explored with arc trench model at $BR = 1$ using thermal image and thermocouples technique.
Arc trench model provides better surface protection from the incoming hot air especially for lower value of BR (BR=0.5) through satisfy smooth and diffusive maxing flow over the plate compared with cylindrical holes model.

(3) Thermal image camera shows quantitative understanding of flat plate surface temperature pattern with easy way to extract data analysis.

(4) Transient temperature with different BR for cylindrical holes and arc trench model are captured during first 1500 second until steady state condition.

Nomenclature

| BR  | Blowing ratio: $\rho_c u_c/\rho_g u_g$ |
|-----|-------------------------------------|
| C   | Coolant air (secondary flow)        |
| D   | Diameter of film hole, mm           |
| H   | Hot air                             |
| IRT | Infra-Red Technology               |
| L   | Film hole depth, mm                 |
| Re  | Reynolds number: $\rho_g u_g D/\mu_g$ |
| T   | Temperature (°C)                    |
| t   | Time (sec)                          |
| TWT | Thermal Wind Tunnel                 |
| u   | Free stream velocity, m/s           |
| X   | Horizontal stream wise direction    |
| Y   | Vertical stream wise direction      |
| Z   | Lateral steam wise direction        |
| $\eta$ | Local film cooling efficiency       |
| P   | Density (kg/ m³)                    |

Acknowledgments

The experimental work described in this research was conducted at the laboratories of mechanical department, Engineering Technical Collage, Middle Technical University, Baghdad, Iraq.

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