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RESEARCH ARTICLE - ENGINEERING

Experimental Study of Two Rows Hybrid Film Cooling Holes Over Flat Plate Surface Using IR Technology

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Abstract

The study examines the effectiveness of two rows of hybrid film cooling holes over a plate surface using infrared technology and a thermal wind tunnel. The two rows consist of seventeen coolant injection holes, with nine in the first row and eight in the second row. Two cases were studied: case 1 using cylindrical holes and case 2 using hybrid holes. Both cases had the same cross-sectional area with a hydraulic diameter of 5.3 mm and a forward coolant injection angle of 30° in the streamwise direction. Different blowing ratios (mass flows ratio between the coolant and mainstream) were tested at 0.5, 1.0, and 1.5. The study focuses on evaluating the impact of hole shape with various blowing ratios on film cooling effectiveness. In addition, thermal images of the test surface were taken via an infrared camera after reaching a steady state. The results indicated that at a blowing ratio of 0.5, there was a significant enhancement in film efficacy, with a decrease in the test surface temperature of the cylinder and hybrid hole cases by 31.8% and 35.0%, respectively, when compared to a blowing ratio of 1.0 and 1.5, which had a temperature increase. Therefore, the film cooling effectiveness decreased to 30.9% and 32.4%, and 29.5% and 31.7% for the cylinder and hybrid hole cases, respectively. Additionally, the better overall film cooling effectiveness in this study was achieved by the configuration of the hybrid holes at a blowing ratio of 0.5, which resulted in a film cooling effectiveness of 35.0%.

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Keywords: Film Cooling; Cylindrical Holes; Hybrid Holes; Infrared Technology; Film Cooling Effectiveness.

1. Introduction

To realize more power and increase improve the thermal efficiency of the modern gas turbine, it is essential to increase the inlet temperature of the turbine. On average, this temperature is increased continuously until reached about 2000°k for a modern gas turbine [1]. This progress was made possible in particular thanks to the research efforts in the field of more resistant materials and alloys at high temperatures, which increased the temperature of blade operation has increased from 1353 to 1453°k. Along with these improvements, the techniques of cooling were introduced and evolved into more complete and more complex systems for the blades uncooled, which have seen the successive appearance of forced internal convection systems such as impingement cooling. Also, protection by external cooling such as film cooling, or even methods of surface treatments acting as a thermal barrier [2]. Air film cooling is the technique most commonly used in industry. In such a situation, cold air is supplied from the compressor to the turbine blades. Cold air is ejected through rows of holes after passage inside the blade, forming a protective film over the surface. The major objective of film cooling is to make a blanket from the coolant injection over the surface blade to protect it from high temperatures [3]. Many efforts have been made to optimize this film cooling technique; the single row of the film cooling holes concept has not been applied in the real turbine blade design. Therefore, researchers studied the effect of characteristics of two-row film cooling holes. Goldstein and Jabari [4] described the effect of two rows of coolant holes on the distribution of temperature over the test plate. The two rows provided good protection to the surface from high temperatures, resulting in higher film cooling effectiveness (FCE) than that of a single row, with an increase of 3% and 22% for blowing ratios (BR) of 0.2 and 0.5, respectively. Ghorab et al. [5] examined an experimental study of a hybrid hole cooling method using cylindrical, fan, and mixed-hole shapes for film cooling. The reduction of heat flux on the cooling surface and the relative efficiency of the film cooling were the focus of this study. The results showed that the hybrid approach improved both the midline and spanwise averaged film cooling effectiveness by 70% and 50%, respectively, compared to other film hole configurations with different blowing ratios. Abdelmohimen et al. [6] carried out an effective cooling study of two rows using simple and compound hole angles. A cylindrical-shaped hole was used in this study at a fixed injection angle of 30°. According to the findings, the simple-simple-staggered holes had higher FCE than compound angle staggered holes. Shu et al. [7] focused on the interaction between flow through staggered holes for two rows and compared the first and second rows and their effect on the cooling performance of cylinder holes. The second row was more contributing to increasing the average spanwise effectiveness of film cooling by 35% at BR 0.5. H.A. Daud and M.F. Mohmed [8] studied the

Nomenclature & Symbols			
FCE	Film Cooling Effectiveness	D,d	Diameter of Film Holes (mm)
BRs	Blowing Ratios	D_h	Hydraulic Diameter for the Elliptic Holes (mm)
IRT	Infrared Technic	°K	Temperature
$\bar{\eta}$ _sw	Average Spanwise Film Cooling Effectiveness	x	The Streamwise Direction Along the Flat Plate Surface
$\bar{\bar{\eta}}$	Overall Film Cooling Effectiveness	y	Vertical Direction on the Surface Plate
THCs	Thermocouples	z	Spanwise Direction Over Test Plat

effect of film cooling hole configuration on a flat surface's performance. The hole configuration performance demonstrated a better surface effectiveness of about 1.6% and 1.2% for rotated triangle and square models, respectively, compared to the cylindrical holes model at BR = 1.0 K. Singh et al. [9] studied experimental film cooling holes for one row of short cylindrical holes over a flat plate with different injection angles (15, 30, 40, 60, and 90°) and two blowing ratios (0.5 and 1.0). Moreover, the study focused on the effects of length-to-hole ratio (L/D) ranging from 1 to 5. Infrared technology was used to measure adiabatic wall temperature. The results showed that short holes with L/D < 3.5 with θ = 15° were found to be the best for achieving higher effectiveness, and with the longest holes, L/D = 5 with θ = 30°- 45° gave the best film cooling effectiveness in the literature. In this study, θ = 45° had higher FCE for BR = 0.5. K. Kusterer et al. [10] studied the effect of two-coolant injection of cooling air to enhance film cooling. A.A. Naji et al. [11] studied the assessment of a coolant jet over a flat plate surface with two staggered rows of holes using infrared technology. Two-hole shapes were used (an elliptical hole compared with a cylindrical hole). The results showed that the elliptical hole shape had the best film cooling effectiveness for three blowing ratios (0.5, 1.0, and 1.5), especially for BR = 0.5, which was 40%.

This study uses experimental IRT at a 30° angle of injection to measure the effect of the coolant jet with direction in forward staggered rows of holes on a flat plate surface. So, two different hole configurations were used cylindrical and new hybrid hole shapes with the same cross-sectional area. Additionally, the study seeks to assess robust IRT as a trustworthy and effective tool for predicting cooling efficiency at various BR by contrasting the findings with earlier work that has been published.

2. Test Plate Cases

The schematic of geometrical the test plate is shown in Fig. 1, There were two models used in this study, as indicated in Fig. 2, each made of Perspex (Polymethylmethacrylate material) which has a low thermal conductivity (0.19 W/m.°K)[12,13], with dimensions of (240mm*120mm*8mm)for length, width and thick respectively. Each case had two rows of staggered film cooling holes, with the first row (up-stream holes) containing nine holes and the second row (down-stream holes) containing eight holes, to ensure thermal uniformity on the flat plate's surface, all holes have been drilled with high accuracy by CNC machine. The distance between the lateral holes of 12mm, the distance between the two rows of 16mm, and the distance from the beginning of the plate to the first and second rows is 40mm, and 56mm respectively. Two types of holes configuration were tested to understand the film cooling effectiveness of coolant jet direction for cylindrical and hybrid holes over the flat plate surface.

3. Experimental Work

Fig. 3, presents a schematic representation of the experimental system to evaluate two-row film cooling effectiveness on a flat plate surface.

All present experimental tests were conducted inside a thermal wind tunnel (TWT) facility with a low wind speed demonstrated in Fig 4. The experimental system is made up of two ducts: the primary stream flow duct, also known as the "hot stream" duct, and the secondary stream duct, also known as the "coolant injection" duct. The primary stream flow duct includes a centrifugal fan with 1.5kw and 1250m3/min, a divergent-convergent section, a combustion chamber with two groups of staggered mesh heaters at power 9 kW for one group, a control electrical cabinet of heaters, a straight duct for fully developed flow, honeycomb, grid cell, and the test section. The mainstream flow is generated via a centrifugal fan at an atmospheric temperature and the velocity of the fan is controlled by a manual gate. Then the mainstream flow passes through heaters in the settling chamber, contraction section, and straight duct involved of honeycomb and grid cell to give us uniform flow inside it, upon entering the test section. Before the inlet of the test portion, a hot wire anemometer is used to determine the speed of the primary flow. The secondary flow duct consists of, a compressor to produce the coolant air, a contraction section, and a pipe connected to the plenum. The velocity of coolant injection is constant at a temperature of 295.15°k.

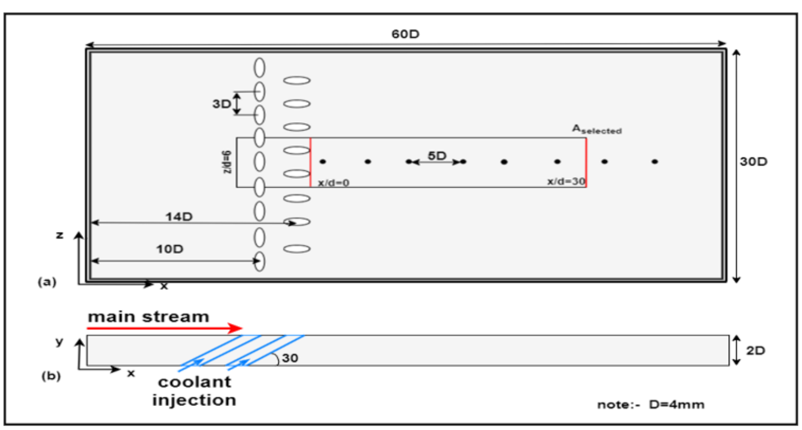

Fig. 1. Geometrical of the test plate with hybrid holes; (a) x-z view, and (b), x-y view

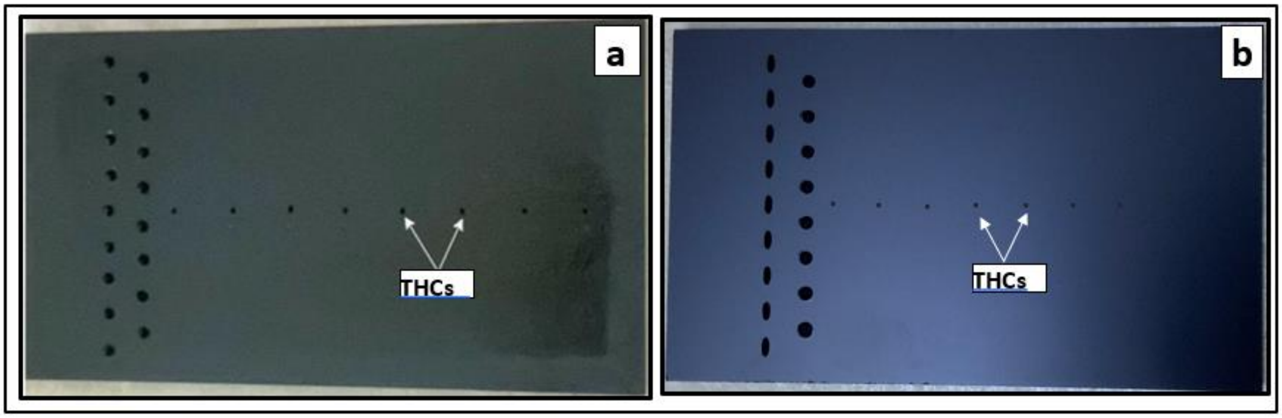

Fig. 2. Flat plate of two test cases a) Cylindrical holes, and b) Hybrid holes

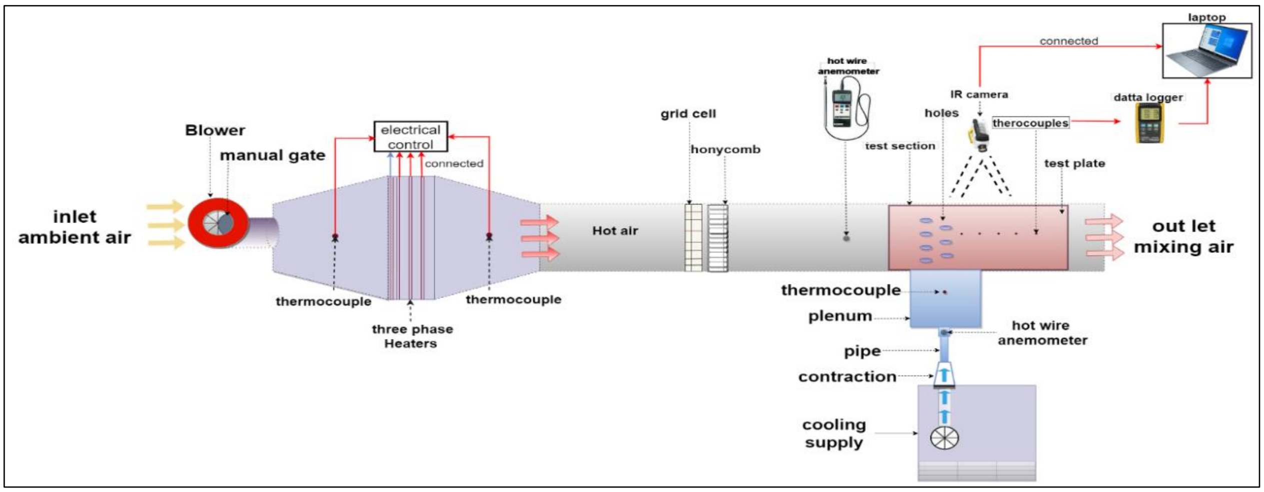

Fig. 3. A diagrammatic representation of the experimental apparatus

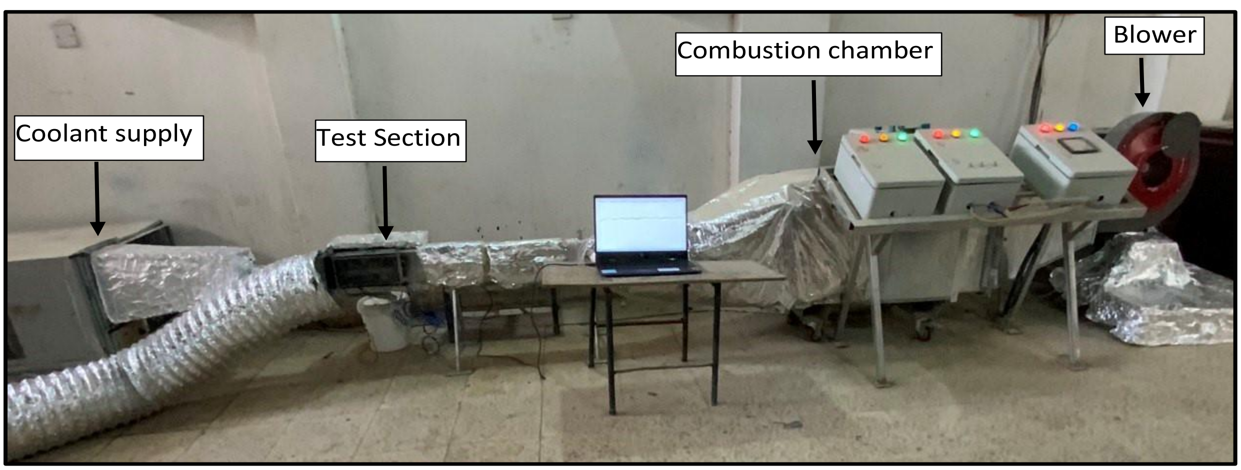

Fig. 4. Experimental test rig

The test section is made of an aluminum plate with two insulated layered, to guarantee that there is no transfer of heat between the surrounding air and the air moving over the test flat plat that has been put within the test section for more reliable results and test plate were made of Perspex. A coating of black paint was applied to the surface of the test plates such that the plates would have an emissivity that was uniformly approximately 0.95. The dimension of a flat plate is 240mm(length),120mm(width), and 8 mm(thick). To determine the temperature of the flat plate, both thermocouples and infrared temperature measuring technologies were used. Eleven thermocouples type-k were used to measure temperature in this study, one for secondary flow temperature was installed in the plenum, two thermocouples were for measuring temperature before electrical heaters were put in the divergent for inside air from ambient and after electrical heaters to the get required temperature. eight thermocouples are put in the middle span of the test plate downstream of the second rows, and this thermocouple is connected to Pico USB TC-08 digital data logger which is connected to a computer to display the change in temperature with time until it reaches a steady-state condition. After that can be evaluated film cooling effectiveness, and take captured by an infrared camera on the surface of a flat plate for measured film cooling effectiveness.

3.1. Test condition and instrumentation

The mainstream velocity supply of the centrifugal fan was changed with the changed blowing ratio in every test condition was 26.2m/s, 13.1m/s, and 8.75m/s for three blowing ratios used of (0.5,1.0, and1.5) with the temperature of 343°k, respectively. Reynolds number $(Re)_{ci}$ for coolant injection with a constant velocity of (11.3) m/s, depended on the same hydraulic diameter for coolant injection holes, for case1 as a cylindrical hole and case2 as hybrid holes was (3904). The density ratio DR (ratio of density between the coolant and mainstream) of the test was equal to (1.17) and the Temperature ratio of (0.31). Three type instrumentation of were used to measure; hot-wire anemometer for velocity, a data logger(Pico USB TC-8 temperature) with a thermocouple to record steady-state conditions and an infrared camera, respectively. For the analysis of temperature distribution over the test surface, as shown in Fig. 5.

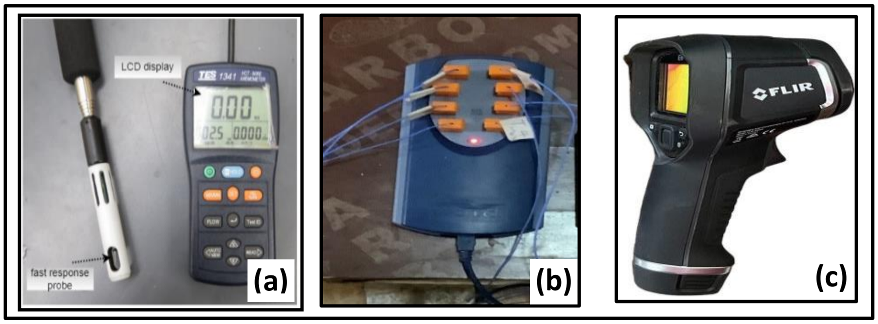

Fig. 5. Measuring of an instrument (a), Hot wire anemometer (b), Data logger and THCs (c), IR camera

3.2. Experimental calculation

Three blowing ratios (0.5,1.0 and 1.5) were measured depending on the density and velocity of the main and secondary streams and were calculated from the following eq. 1.

Blowing ratio (BR) $=\rho_{ci}u_{ci}/\rho_{ms}u_{ms}$ (1)

where $\rho_{ci}u_{ci}$ is the density and the velocity of coolant injection, *and* $\rho_{ms}u_{ms}$ is the density and the velocity of the mainstream.

Spanwise film cooling effectiveness depends on three parameters as shown in the eq. 2.

Local spanwise averaged FCE $(\bar{\eta}_{sw}) = \frac{T_{ms}-T_w}{T_{ms}-T_{ci}}$. (2)

where T_{ms} and T_{ci} is the temperature for mainstream and coolant injection flow, T_w: Average wall temperature of the area selected x/d=30 (divided into 17 small areas) was calculated by IR camera (°K).

overall averaged FCE ($\bar{\bar{\eta}}$)= $\frac{\bar{\eta}\_sw1+\bar{\eta}\_sw2+......+\bar{\eta}\_sw17}{17}$ (3)

4. Results and Discussion

In the experimental work, two types of models were examined. The first case consisted of two rows of cylindrical film cooling holes(baseline), and the second model consisted of two rows of hybrid holes. After that, (8) thermocouples were placed at the centerline along the downstream area of the test plate to record the temperature for 1000 seconds for each of the three blowing ratios of (0.5, 1.0, and 1.5). The temperature of the mainstream rises gradually with time due to air passing through heaters which increased temperature from room temperature to 343.15 °K until reached a steady state condition. For experimental results, an infrared thermal imaging camera (FLIR) was used to capture the temperature of the flat plate surface at various blowing ratios for the three cases, the thermal image of the test plate surface was taken after 20 minutes from the test time when the steady state was reached.

Thermal images were evident by (FLIR E6-XT) type, with a temperature range between (253.15°k to 823.15°k) and a thermal resolution of (43000 measurement pixels), where it can be seen the test plate through the Plexiglas window located at the front of the test section, the pattern showed hot and cool flow mixing at the first and second rows of holes over the flat plate. Fig. 6(a) showed the Thermal image for temperature distribution over the test plate surface for different blowing ratios of (0.5,1.0, and 1.5) for case 1 when compared with BR=1.0 and 1.5. demonstrates that a pattern of lower surface temperatures emerged when BR was set to 0.5. of (327.73° k) this was caused by a broad range of low-spectrum surface temperatures that appeared on average span-wise of downstream cylindrical holes. Figure (6, b) illustrates a thermal image for temperature distribution over the test plate surface for different blowing ratios of 0.5,1.0 and 1.5 for a new model of hybrid hole shape, the pattern showed hot and cool flow mixing at the first and second rows of holes for good, uniform coverage of a test surface downstream. As a consequence of this, a significant decrease in the surface temperature pattern for all three BR, especially at BR=0.5 by (326.12°k).

The FLIR data application was used to analyze the IR picture to refine the flat plate adiabatic surface temperature data. span-wise averaged film cooling effectiveness is shown for three rows beginning from x/d =0 to x/d =30. Each row ranges from z/d =−3 to z/d =3, as shown in the area selected for (Fig. 1). Fig. 7 (a and b) Described average spanwise film cooling effectiveness changed with three BRs of (0.5,1.0 and 1.5) along x/d for case (1 and 2) respectively. as clearly of (BR=0.5) that the maximum value of the average effectiveness at exit holes was $\bar{\eta}\_{sw}$ (48% and 56%) at x/d=0 and then decreased gradually along downstream of the streamwise direction into $\bar{\eta}\_{sw}$ (23% and 24%) at x/d=30 for case (1 and 2) respectively, due to low momentum of coolant injection this will result in the inability to penetrate the mainstream and stay close of the test surface, Therefore, the surface temperature decrease, especially at the outlet of the hole. When the blowing ratio is raised to (1.0 and 1.5) respectively, the ability of coolant penetration also rises for case1 more than case 2 due to the low speed of mainstream and the effect of shape hole on flow, which is evident when the average spanwise FCE drops at x/d 2 by (29%% and 33.6%) and (18.1% and 21.6%)respectively, this allows the coolant to flow farther from the surface, after that, it gradually increases as a result of coolant reattached to the surface when x/d is more than 3.

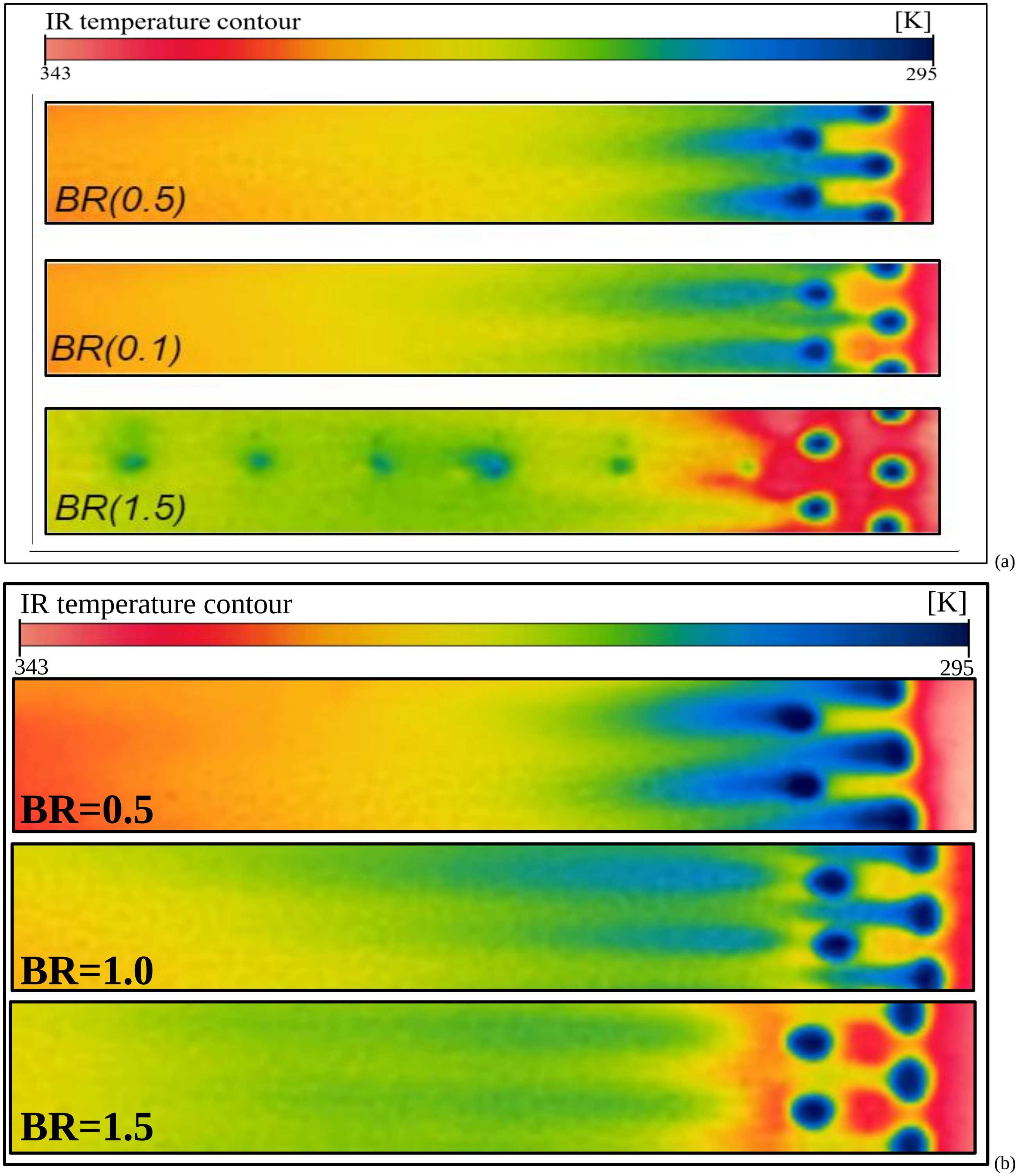

Fig. 6. Thermal image for temperatures distribution over test plat surface for different blowing ratios of 0.5,1.0 and 1.5 by using IRT of a) case1 and b) case2

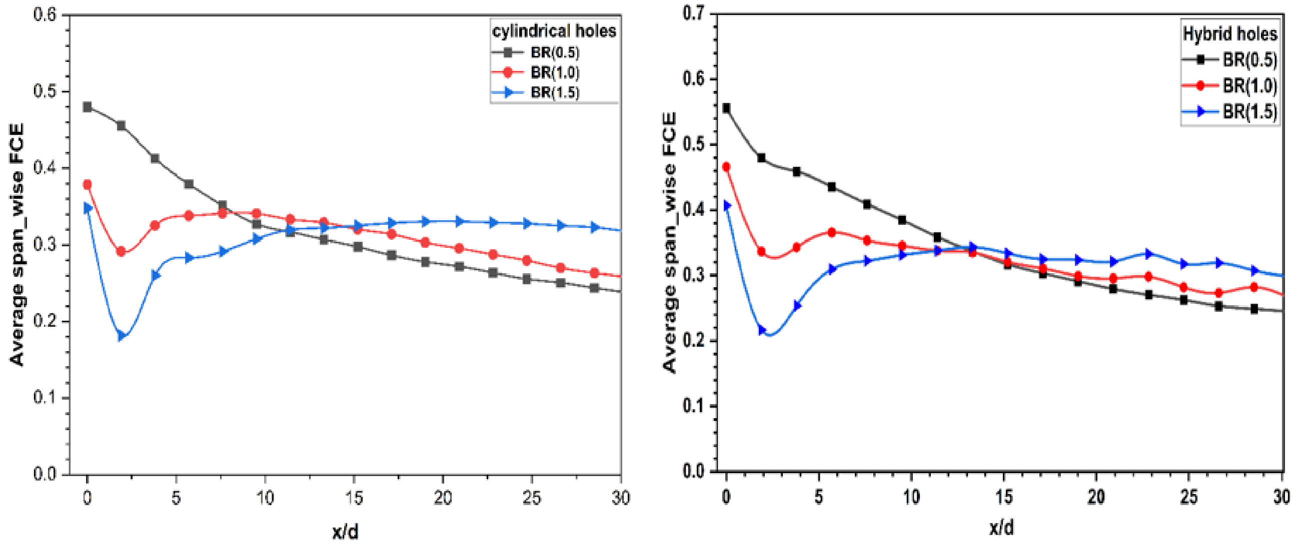

Fig. 7. Average span_wise FCE by thermal camera data (a), cylindrical holes (b), elliptical holes

Fig. 8(a) described the effect configuration of holes shape, as cylindrical holes for (case1) and hybrid holes for (case2) on average spanwise film cooling effectiveness. a good enhancement at FCE for the hybrid hole case was raised about 10 % at x/d =0, above the cylinder hole case for BRs of (0.5), and then the enhancement continues for the hybrid hole along x/d(1<x/d<30) compared with cylinder, due to effect upstream row (elliptical hole) on FCE of hybrid holes this give more spread over the test surface compare with case1. For Fig. 8(b) also hybrid holes case has spanwise FCE slightly more than case1 at an area limited between x/d of 0 to 13, due to low penetration for the hybrid hole, after that approximately the same spanwise FCE until x/d=30.

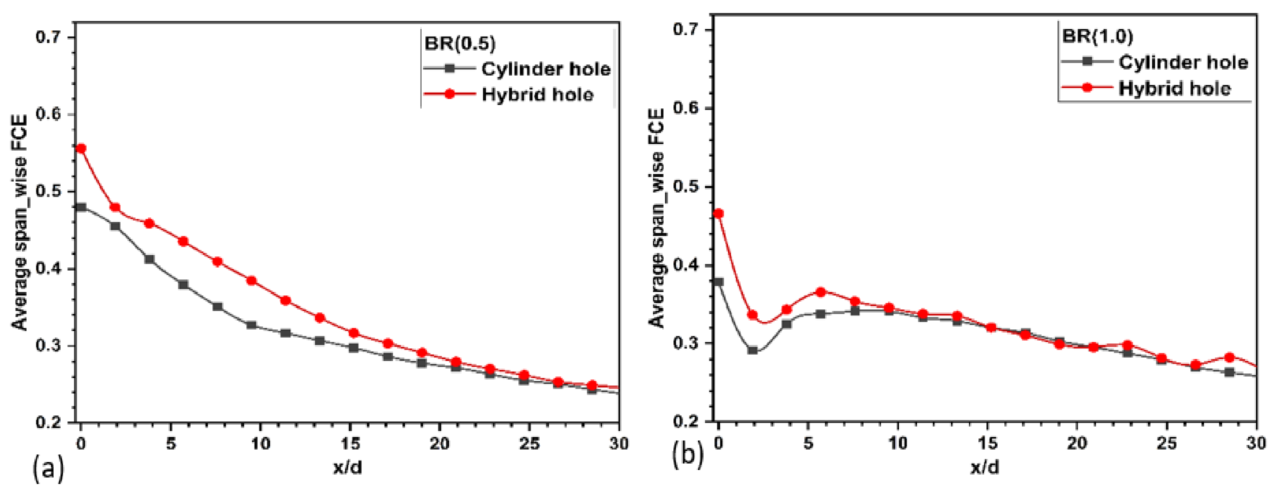

Fig.8 Effect hole average span_wise FCE for case1 and case2 for a), BR of 0.5 and b) BR of 1.0

Fig. 9 displayed the overall averaged film cooling effectiveness($\bar{\bar{\eta}}$) calculated from the values of the local average span-wise film cooling effectiveness ($\bar{\eta}$ _sw) for the area selected. the results of the experiments, which were analyzed by IRT, showed of increase in overall FCE for the average limited area for different ratios (0.5,1.0 and 1.5), with case2 (two rows as elliptical holes for the upstream hole and cylindrical for downstream holes) by (4%), due to good distribution of mixing between two flows on the surface of the test plate, performing better than case1 in this regard (two rows of cylindrical staggered holes). Results of present work at BR equal to (0.5) have good agreement with published work of experimental study [4] and numerical study [6] of 12% and 18%, respectively. as shown in figure (10). A detailed comparison between the present study and published work is described in Table 1.

Table 1. Comparison between test plates was used

Type of studied	Material test plate	Diameter (mm)	Area work(mm)	Blowing ratio
Experimental present work	Perspex	4	240*120	0.5
Experimental past work [4]	Brass insulate by wood	13	400*116	0.5
numerical past work [6]	Perspex	10	300*150	0.5

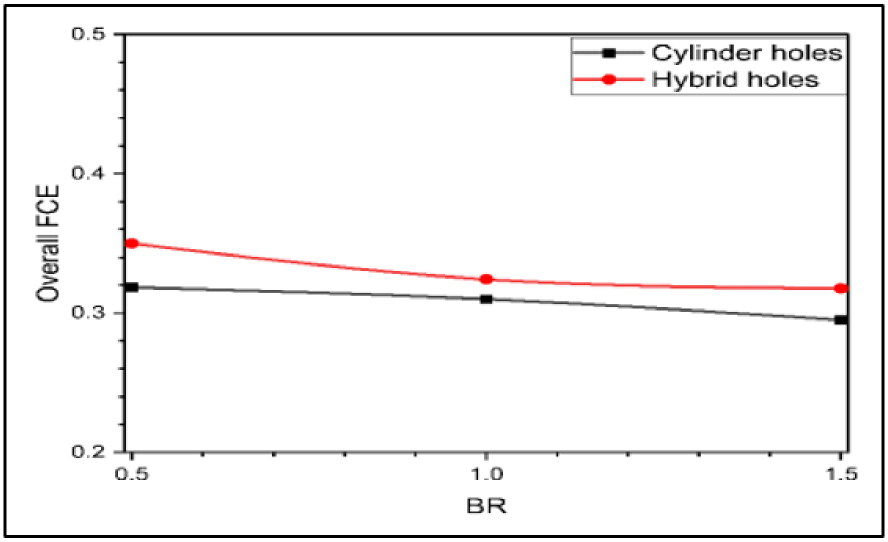

Fig. .9. Effect of different blowing ratios on overall film cooling effectiveness

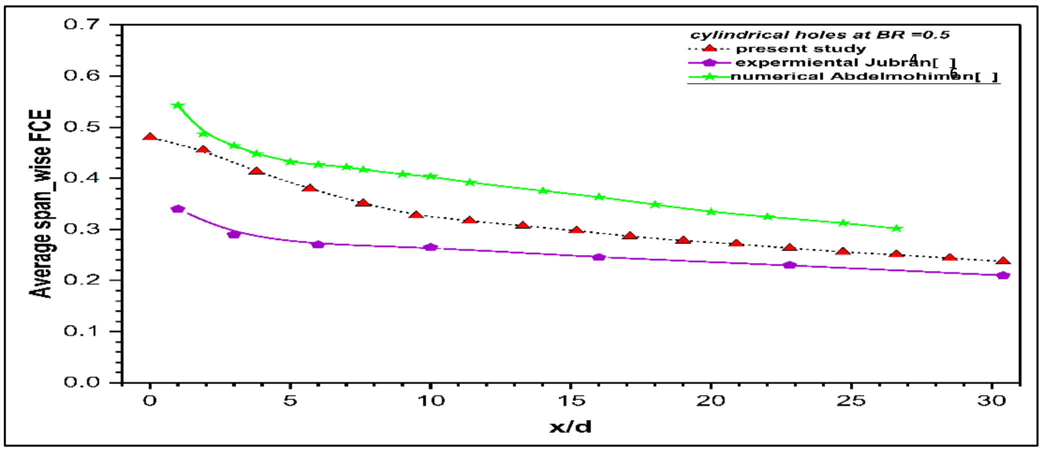

Fig. 10. Validate spanwise FCE for present work with literature results of ref [4] and [6]

5. Conclusion

The flat plate surface temperature pattern has been portrayed clearly and concisely using an IR thermal imaging camera. In addition to co empirically confirming the impact of changing the blowing ratio empirically, in this study cylindrical and elliptical film cooling holes are used in this study.

1. The best enhancement in overall film cooling effectiveness was for hybrid holes of (35.0%) compare with cylindrical holes of (31.8%) at the blowing ratio of 0.5.
2. Tow row of staggered hybrid holes with good coverage of coolant injection over the surface of the test plate to protect it from the hot mainstream, for different blowing ratios of (0.5,1.0, and 1.5).
3. For blowing ratios (1.0 and 1.5) when penetration increased, the temperature of the test plat was increased due to the coolant injection don't attach it, due to that the film cooling effectiveness decreased to 30.9% and 32.4%, and 29.5% and 31.7% for the cylinder and hybrid hole cases, respectively.
4. The thermal image camera displayed a quantitative comprehension of temperature patterns on the test surface while providing a simple method to extract and analyze data.
5. Good agreement between experimental and numerical previous studies with present work of 12% and 18%, respectively.

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