Investigating Cooling Effect with Compound Angle on the Combustion Chamber Wall Temperature

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Abstract: Increasing the temperature of the turbine entrance gases increases the efficiency of the gas turbine cycle. Under these conditions, the combustion chamber wall temperature also increases, while there is no high temperature resistance alloy fitted with air motors. Therefore, it is necessary to use cooling methods to reduce the wall temperature. In this study, the cooling effect with compound angles investigated on the combustion chamber wall temperature. The three-dimensional combustion chamber k-ε is modelled under the conditions of the input speed and the turbulence model in the ANSYS Fluent software. Inlet air is injected from the cooled holes to the mainstream with compound angle, where the cooling flow angle is constant with the 30° horizontally, and the lateral angle changes from Beta =0 up to Beta=60 degrees. The combustion chamber has two flat planes and two sloping plates, in which the arrangement of cooling holes is different. The results show that this method better distributes the cooling air on the wall surface and covers the space between the cooling holes, especially on flat plates. With this method, the number of cooling holes and the amount of air used to cooling can be reduced.

Keywords: Combustion Chamber, Compound Angle, Film Cooling, Wall Temperature

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1 INTRODUCTION

One of the major problems for engine designers is the design of a combustion chamber with high temperature output and long service life. Therefore, the maximum wall temperature and cooling of the liner wall are important in order to increase the life span of the combustion chamber. However, there are several methods to reduce the temperature of the liner wall of the combustion chamber, but usually a laminar cooling method used in which air is injected into the combustion chamber through a series of holes on the wall. In this method, a thin film of low temperature air was placed between the liner wall and the high temperature flow, which protects the combustion chamber wall and prevents corrosion and excessive temperature rise. In the area near the outlet of the cooling holes, the temperature is the lowest and the temperature increases with the distance from the holes. In addition, this cooling air does not have much effect on the hot air generated by the combustion [1].

The geometry of the cooling holes and the air injection angle has a great influence on the cooling performance. The study of the cooling effect of the jet angle on the filmed cooling on a flat plate indicates that the cooling performance decreases if the air inlet angle of the cooling hole increases over the plate. Coulli and Bogdar examined the cooled coat effect for two cooling holes at angles of 35 and 55 degrees relative to the plate [2]. The results showed that the film cooling effect at the angle of 55° for I=0.16 and 0.63 decreases by 10% and 30%, respectively. Foster and Lampard investigated the cooling effect of cooling holes at angles of 35 and 90 [3]. Their results showed that at the angle of 90 the effect of the filmed cooling in the blower ratio of 0.5 decreases, but in the ratio of the blower, 1.4 the film cooling effect increases. Leo and Zhang investigated the effect of angle digression of cooling effectiveness holes on the temperature of combustion chamber wall. Results showed that digression holes distribute much better and finally the wall temperature and cooling effectiveness develop but the pressure dropping increase [4]. Kouset al. investigated the numerical value of the film cooling effect on several flat and curved plates. The results showed that the film cooling function depends on the shape of the holes, the curvature plate tilt and the blowing ratio [5]. Goldstein et al. investigate the effect of layer cooling on one row holes cooling effectiveness with the compound angle that its blowind ratio was variable from 0.5 till 2 [6]. Their results showed that in the low blowind ratio at 0.5 till 1 has no much differences oppositely with high blowind ratio, laterally averaged mass transfer coefficient for both normal and compound holes has no much differences.

Goldstein et al. investigated the effect of different parameters on the wall temperature, they investigate the effect of temperature, speed ratio, distance between holes and spraying angle. Their results showed that the both parameters of temperature and speed of cooling effectiveness ratio have more effect on the temperature of wall [7]. Hay et al. investigated the effects of cooling films on the heat transfer coefficient on a flat plate with zero mainstream pressure gradient [8]. Ammari also investigated the cooling current density ratio effect on the heat transfer in geometry similar to geometry [9]. Their results showed that increasing the density ratio from 1 to 1.52 in a mass Debi of 0.5 has no effect on the heat transfer. Halla et al. investigated the effect of film cooling for different values of L/D and in different angles of diffusion. Their results showed that the geometry of the holes in the cooling and the angle of air injection had a great influence on the cooling performance and two linear and chess layouts are the best layouts in a film cooling process [10]. Occasionally, the cooling holes tilted towards one side toward the mainstream, which is called the compound-spraying angle. The use of this method makes the area more covered by the cooling air and increases the heat transfer coefficient. Mayet et al. investigated the effect of film cooling in two different arrangements for holes with compound angles [11]. Their results showed that cooling for chessboard holes is better than linear alignment. Juvenger and Brown [12] and Liggery et al. [13] reviewed the film cooling for two rows of composite angled cooling holes. Juvenger and Brown experimentally investigated the effect of the distance between the holes, the hole column spacing and the cooling hole angle on the different blow ratios. Their results showed that the use of holes with a compound angle provides better cooling rather than holes that are only in one direction of the angle. Schemed et al. examined the effect of hole spacing on cooling for p/d=3 and p/d= 6 [14]. They used holes angled at 35 degrees to the plate 0 and 60 degrees to the flow direction. The results showed that the cooling effect in the case of p/d=3 is twice of p/d=6. Bladauf et al. [15] later examined his results. They did their research on p/d = 3, 2, 5. Their results showed that for a blow ratio greater than 1.2 at p/d=2, a better film cooling blow ratio was done while p/d=3 and p/d=5, the cooling of the film does not work well.

Vakil et al. [16] examined the flow and temperature field in an air engine combustion chamber. In addition, Kianpour et al. [17] examined the effect of the geometry of the cooling holes in the Vakil's combustion chamber on the temperature of the outlet and the wall temperature. Their results showed that using multiple micro holes would improve instead of holes with larger diameters and fewer cooled ones.

The researches that have been done so far have investigated cooling on a flat or sloping plate or the combustion chamber wall. In this present study, the cooling effectiveness on the wall of combustion chamber has flat and slopping plate and the holes of cooling has different arrangement according to each other so it is more comprehensive in comparing with previous ones was investigated. The effect of film with compound angel on the wall temperature of the combustion Vakil's chamber is studied. A cooling stream is fed into the mainstream through the cooling inlet holes. The inlet airflow angle of the cooling holes is 30 degrees horizontally and the lateral angle changes from 0 to 60 degrees. In the current work, the effect of cooling effectiveness angle on the wall of flat and slopping plate that has different arrangement and the effects of this method on the average wall temperature, temperature gradient, and cooling flow on the wall surface have been investigated.

2 MATERIALS AND METHODS

In this study, the combustion chamber of the Vakil'set al. [16] is simulated in three dimensions. The combustion chamber was simulated with 111.8 cm width and a 156.9 cm long. Other characteristics of the combustion chamber are presented in "Table 1".

Table 1 Combustion chamber specifications [16]

Geometric characteristics of the enclosure		
Characteristic	Dimensions	Description
Combustion chamber width	111.8	According to fig.1
Combustion chamber height	99.1	According to fig.1
Combustion chamber length	156.9	According to fig.1
Input cross section	1.11	According to fig.1
Outlet cross section	0.62	According to fig.1
Reduce cross-sectional input to output	1.8	According to fig.1
Contraction angle	15.8	Start from X=79.8

The simulated combustion chamber is shown in "Fig. 1", the combustion chamber has a main input and four consecutive cooling plates, the second and third plates have diluent holes. These plates are positioned so that the top and bottom of combustion chambers are similar.

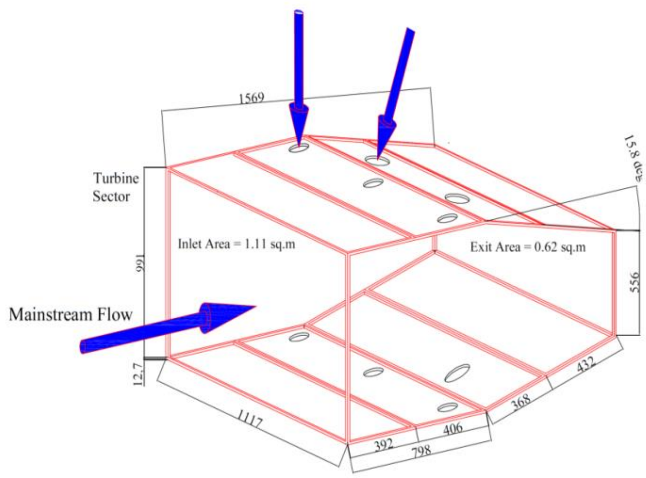

Fig. 1 Combustion chamber [13].

In "Fig. 2", the size of the plates of the cooling holes of the combustion chamber is shown. The first and second plates are flat, but the third and fourth plates are sloping.

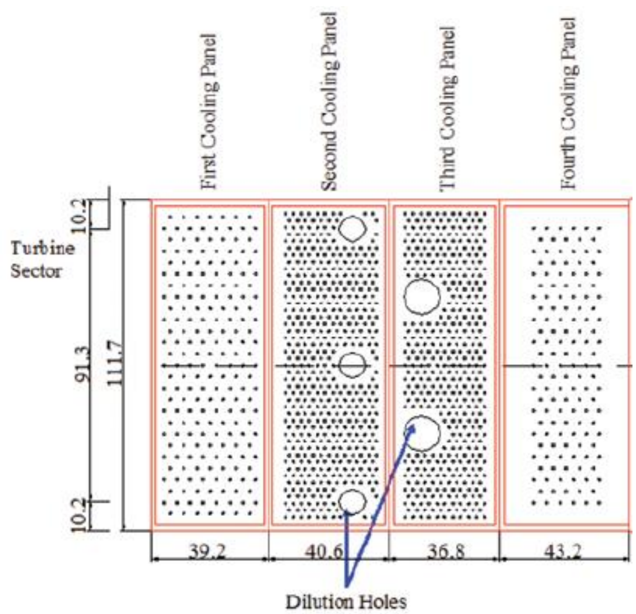

Fig. 2 Dimensions of cooling plate [16].

The cooling holes are located in the angle of an equilateral triangle and in the same intervals in a chessboard. The hole arrangement is shown in "Fig. 3". The diameter of the cooling holes is 0.760 cm and they are 30 degrees higher than the horizon. The distance between the cooling holes is given in "Table 2".

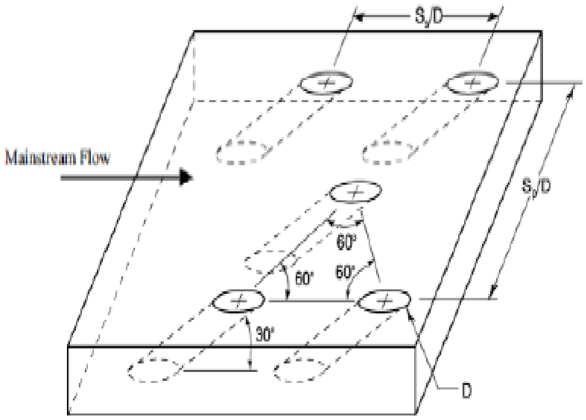

Fig. 3 Cooling holes arrangment [16].

Table 2 Distance between cooling holes [16]

	S_P/D	S_S/D
Plate 1	10.1	5.8
Plate 2	6.1	3.5
Plate 3	6.1	3.5
Plate 4	10.1	5.8

To analyse flow field, plates 1p and 2pand 1s were used. This plate extends from z=0 to z=10 and covers half of the width of the combustion chamber. The plate 2p is embedded in x=1.1 and has been expanded from z=0.90 to z=0.22 along the vertical axis. In “Fig. 4”, these plates are shown.

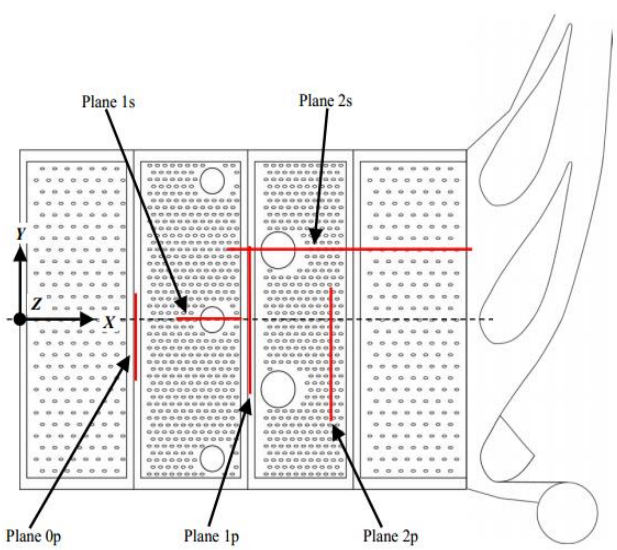

Fig. 4 Plates used to measure the flow temperature [16].

The inlet airflow to the compartment has a different density with the air input from the cooling holes, in “Table 3” the flow characteristics of the inputs to the compartment are shown.

Table 3 Specifications of input streams [16]

Flow input	Density (Kg/m^3)	Temperature (K)	Input velocity (m/s)
Main Flow	1	332	1.62
First Cooling	1.12	295.5	4.58
Second Cooling	1.12	295.5	4.58
First diluent	1.12	295.5	17.29
Third Cooling	1.12	295.5	4.58
Second diluent	1.12	295.5	8.65
Forth Cooling	1.12	295.5	4.58

In this research, the cooling current effect with compound angle on the wall temperature in four different conditions has been investigated. In “Table 4”, different modes of intake air are provided from cooling holes.

Table 4 Different modes of intake air with compound angles

Cooling flow	α	β
1	30	0
2	30	30
3	30	45
4	30	60

3 GOVERNING EQUATIONS

In the forthcoming research, the flow is considered to be confusing and incompressible. The momentum transfer equation is discrete and the Second Order Upwind is defined as follows.

$$\frac{\partial}{\partial t}(\rho_{u_i}) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho_{g_i} + \vec{F}_i \qquad (1)$$

The energy equation for the current stream is also written as follows:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(u_i(\rho E + P)) = \frac{\partial}{\partial x_i}\left(K_{eff}\frac{\partial T}{\partial x_i} - \sum_j h_j J_j + u_j(\tau_{ij})_{eff}\right) + S_h \qquad (2)$$

The continuity equation is also defined as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x_j}\frac{dx}{dt} + \frac{\partial \rho}{\partial y}\frac{dy}{dt} + \frac{\partial \rho}{\sigma z}\frac{dz}{dt} = -\rho(\nabla . V) \qquad (3)$$

Simple algorithm is used to solve the Navierstock equations. In this method, the relationship between speed and pressure is corrected to enforce the mass survival law and obtain the field of influence.

For modelling, the RNG model belonging to the renormalization group was used. This model is similar to the standard model, while it also includes modifications. Correction of E, including adding the rotation effect in turbulence, used an analytical formula for the prantel number, which makes it more reliable than the standard method for most currents, especially for rotational jets. This model is one of the derivatives of the Navier Stokes equation and the results obtained in this model are different from the standard method, which is due to the same equations in K and Ɛ equations. The RNG model is defined as Equations 3 and 4.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial k}{\partial x_i}\right]+P_k-\rho\varepsilon \quad (4)$$

The second order upwind method is used to discriminate k-e equations. This method has a precision of order 2 and is more suitable for triangular networking (irregular).

4 VALIDATION

In order to determine the accuracy of the results, numerical and experimental results should be compared. In order to validate the modelling method, the numerical results of this work are compared with the experimental Vakil's work et al. [16] in 2005. Kianpour et al. also simulated this combustion chamber.

To check the flow field, 1p, 2p, and 1s plates were used. The plate 1s along the center of the second row dilution hole is drawn along the compartment. In "Fig. 5", the temperature contour is shown on the plate 1. By using this plate, it is possible to check the flow behavior in the second row of diluent jets. It is observed that the airflow from the second diluent holes leads to increase in turbulence and ultimately complete combustion in this area.

The plate 1p is placed down the first row of diluent holes. This plate is used to check the interaction of the main flow plate with the dilution airflow. In accordance with "Fig. 6", the temperature is low near the wall due to the suitable filmcooling, and the temperature rises gradually as the wall drops. Also, in the center of the chamber, the temperature has decreased due to the interaction of the main current with the air dilution air.

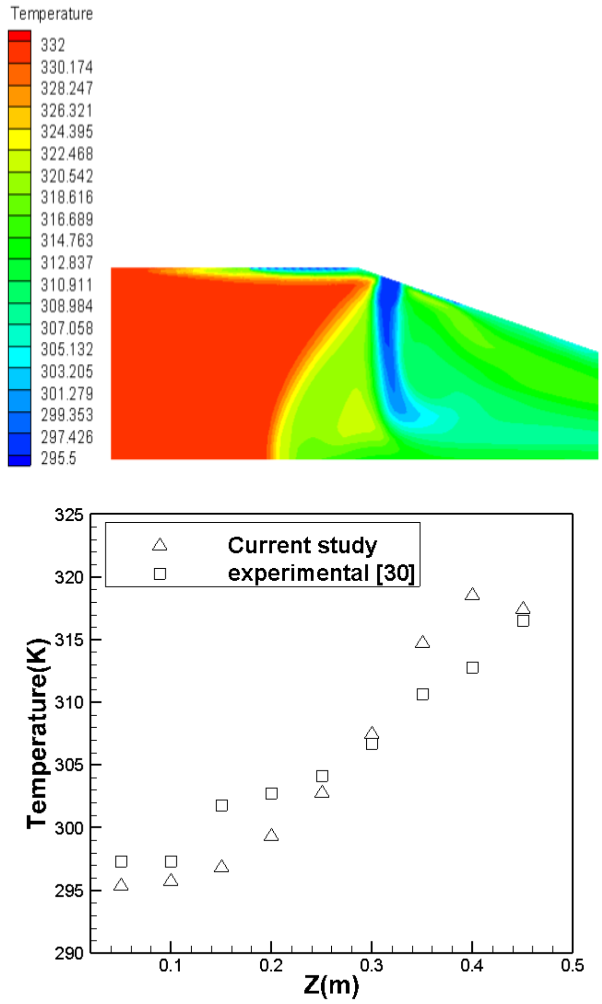

Fig. 5 (a): Temperature contour on plate 1s and (b): Temperature changes on plate 1s along X / L = 0.55.

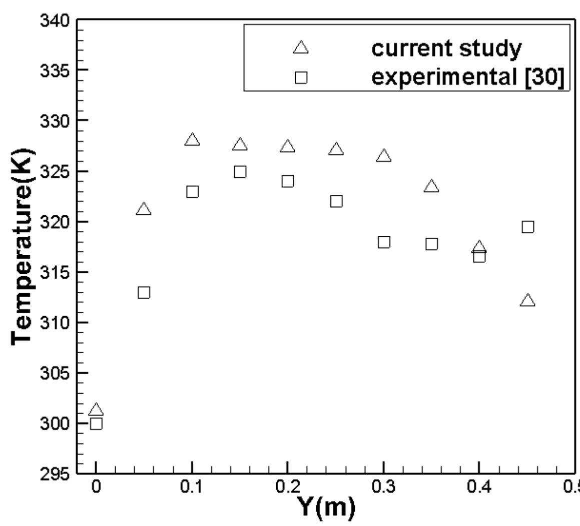

Fig. 6 Temperature changes along Y along the 1p plate along Y / W = 0.25.

In “Fig. 7”, the temperature change diagram in the plate 2p is shown in Y/W=0.25. The page 2p is located at the bottom of the second row of the diluent holes. Using this plate, we can examine the interactions of the intake air from the dilutions and mainstream holes. Comparing the results of present work and experimental work shows that modeling has a good accuracy.

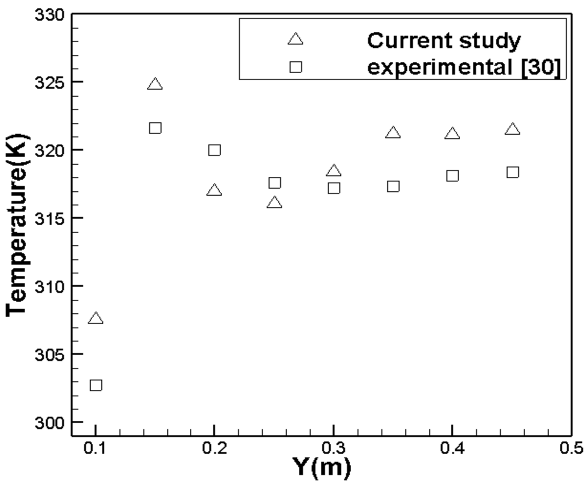

Fig. 7 Temperature changes in 2p plate along Y / W = 0.25.

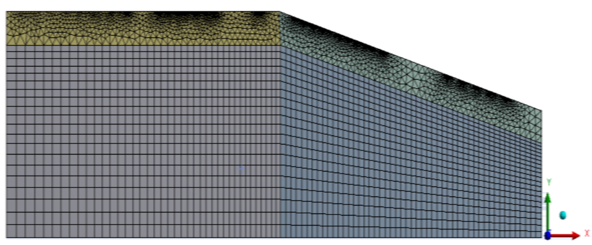

Fig. 8 Meshed combustion chamber of the turbojet engine.

5 NUMERICAL SIMULATION OF COMBUSTION CHAMBER

The simulated combustion chamber consists of a main input and four consecutive cooling plates, that the second and third plates have diluent holes. Due to the symmetry of the chamber, only a quarter of it was modelled. The boundary condition of the speed was considered for inputs and the pressure was considered for exit. For turbulence modelling, the k-e disturbance model, RNG model, and simple solving method were used. The number of cells used can change the accuracy of the calculation. Increasing the number of cells can increase the accuracy of computations, but also increases the time of calculations. The number of cells should be such that, in addition to providing the calculations with acceptable accuracy, there is also a time to calculate quantitatively. For networking geometry, an irregular (triangular) grid was used to reduce the time of calculations in addition to improving. As shown in “Fig. 8”, in the cooling hole area, the fine mesh size is used to increase the accuracy, and the size of the tubes increases as holes are removed.

In “Fig. 9”, the temperature changes along z = ... along the chamber are shown relative to the changes in the number of cells. As shown, the amount of temperature in the number of cells 1743528 with a temperature of 2643187 shows a difference of about 3 degrees, but the temperature difference in the number of cells 2238572 with 2643187 is less than 0.5 degree. So, in the calculation, the number of 2238572 meshes was used, because in addition to the accuracy, it can also reduce the computational time.

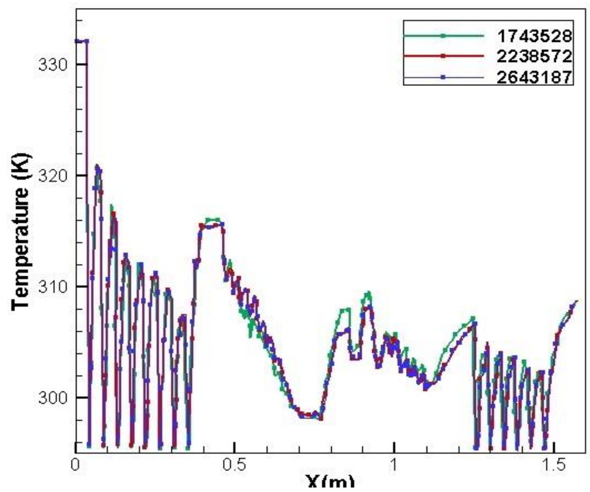

Fig. 9 Changes in temperature along Z = ... along the chamber relative to changes in the number of tuberculosis.

6 NUMERICAL RESULTS

Cool air is injected into the chamber from coolant holes that align 30 degrees horizontally and the angle of the holes varies from 0 to 60 degrees. In Figure 10, cool air flow lines are shown for the first enclosure wall. As shown in Fig. 10, at a 0 ° angle, in the absence of a compound angle, the flow moves only along x, but when the air enters with a hole angle, cooling is done in z-direction. Due to the fact that the main flow of air is in line with X, the coolant holes continue to flow through the mainstream, leaving the cooling air in the direction of the X.

In “Fig. 11”, the temperature of the first and second wall of the chamber is shown. The first and second walls are flat and the gap between the holes of the walls of these walls is different. In the first wall in Beta = 0, cooling is performed only along the holes and no cooling is made between the holes. In the first wall in Beta = 0, cooling is performed only along the holes and no cooling is made between the holes. Also, at the end of the first wall, after the cooling holes in the Beta=0 and Beta=30, the wall temperature is lower than the other. Also, in beta = 30, the wall temperature is more uniform than other states.

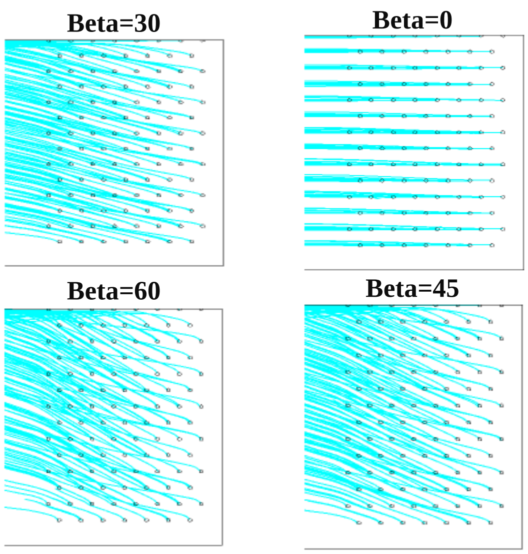

Fig. 10 Flow lines of first wall cooling air.

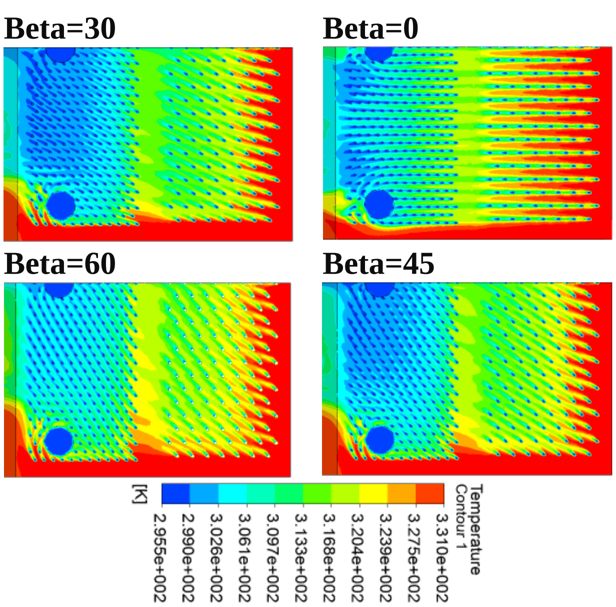

Fig. 11 Cantor temperature of the first and second walls.

The second wall in the Beta = 0 state also has a low temperature between the holes, which is due to the reduction in the distance between the holes as well as the cool airflow of the plate, which covers the holes. It can be seen that in the second wall in beta = 60, the wall temperature is more uniform than other conditions. The results also show that cooling with a compound angle for the flat surface of the area covers more area. Cooling air is spread on the wall surface.

"Fig. 12" shows the temperature of the third and fourth walls of the chamber. The third and fourth walls were sloping and the distribution of cooling air in them is different from the first and second walls. The results show that by increasing the lateral angle at the end of the second wall and the beginning of the third wall, the high temperature flow penetrates the left, and causes the temperature of this area to increase. We see the same at the end of the third wall. In the third wall in Beta = 60, the wall temperature is more uniform than other cases but the low temperature zone is less.

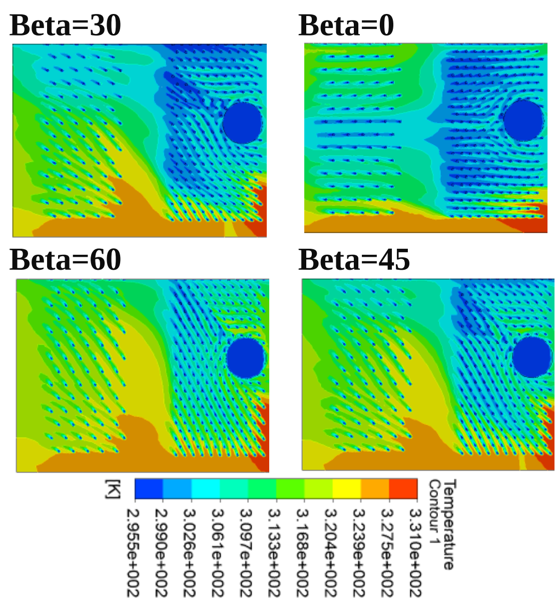

Fig. 12 Temperature cantor of the third and fourth walls.

In Beta = 0, cooling in the fourth wall is better than other cases. It is also observed that the area between the holes is well cooled unlike the first wall. This is due to the cool flow of holes in the third wall that covers the area. Accodringly, the arrangment of holes in the first and second walls are in the opposite direction to the third and fourth walls. The results showed that placing a wall with multiple cooling holes have less space between cooling holes before a wall with fewer holes and more spacing, In addition, it reduces the temperature of the first wall and It can cover the distance between the holes in the second wall and ultimately the cooling in both walls is well done.

In order to better determine the performance of the cooling with compound angle; the temperature will be investigated along x in several different Z. In "Table 5", the coordinates of the lines and in "Fig. 13" direction of lines is shown.

Table 5 Z1, Z2 and Z3 coordinates

lines	Coordinates along Z axis
Z1	0.3838
Z2	0.37088
Z2	0.34542

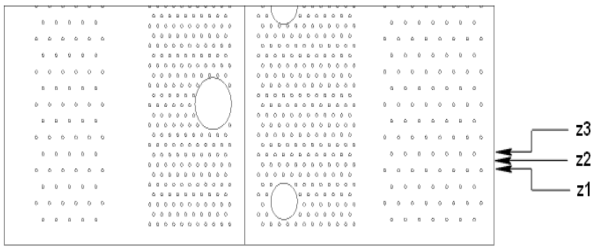

Fig. 13 Locations of Z1, Z2 and Z3 lines.

In "Fig. 14", the temperature graph along the line z1 is shown. This line passes through the middle holes of the first wall and the area between the holes of the second wall. This line passes through the middle holes of the first wall and the area between the holes of the second wall. Due to the fact that in Beta = 0, unlike cooling with the compound angle, the whole flow of cooling air flows along X, It makes it easier to cool down the holes in the first wall. It is observed that along the line Z1 at the end of the second wall, the temperature increases with increasing lateral angles. This is due to the high current flow that penetrates the right, So that in the Beta = 60, we have the highest temperatures in the area.

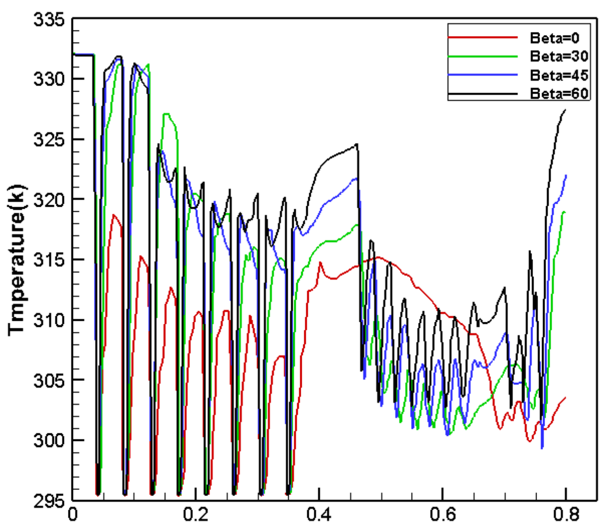

Fig. 14 The first and second wall temperature graphs along the Z1 line.

In "Fig. 15" The temperature graph is shown along the line z2. This line passes through the area between the holes in the first wall and the middle of the holes in the second wall. The results show that in the first wall in the hole area, the wall temperature for Beta = 0 is the highest, and the cool air cannot cover the area between the holes. But in the second wall in the direction of the holes for Beta = 0, cooling of the other modes is better.

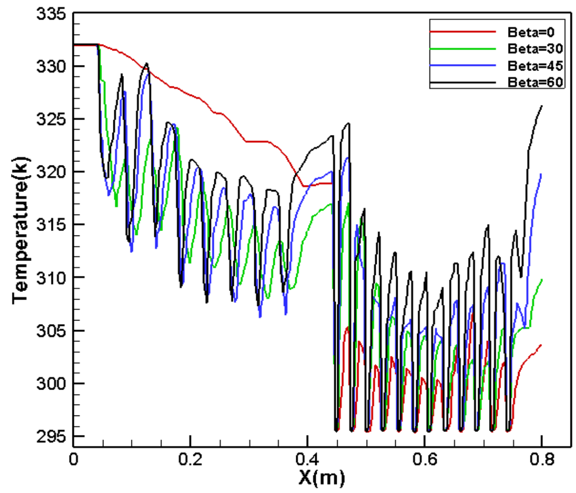

Fig. 15 The first and second wall temperature graphs along the Z2 line.

In "Fig. 16" the temperature chart is shown along the Z3 line. The Z3 line passes through the middle of the first and second row cooling holes. The results show that in the second plane of the plate, cooling is done in the cooler holes in Beta = 0 and increases with the increase of the lateral angle of the wall temperature along the holes.

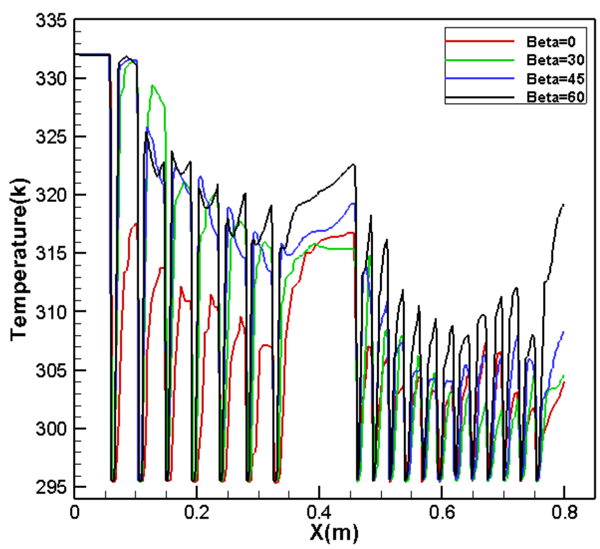

Fig. 16 The first and second wall temperature graphs along the Z3 line.

In "Fig. 17", the temperature chart is shown along the Z1 line. The Z1 line passes through the area between the holes in the third wall and the middle of the holes in the fourth wall. The results show that in line with this line on the third plate, in the area of the hole, with the compound angle of cooling decreases, but along the lines on the fourth plate, cooling is not a function of the lateral angles and has the same results at different angles of the sides.

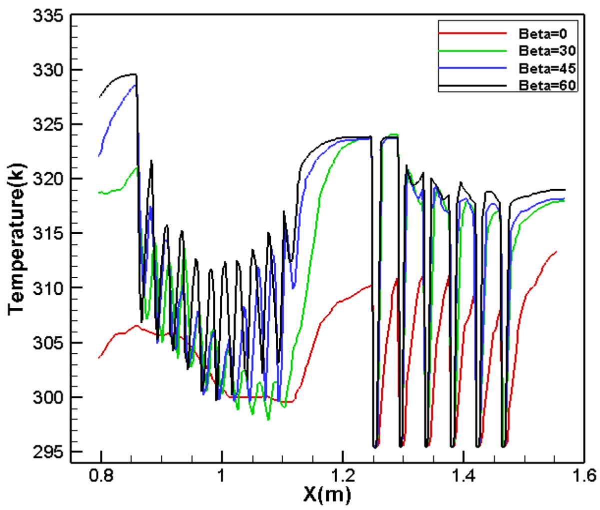

Fig. 17 The third and forth wall temperature graphs along the Z1 line.

In "Fig. 18", the temperature chart is shown along the Z2 line. The Z2 line, in contrast to the Z1 line, first passes through cooling holes and then between cooling holes. It can be seen that by reducing the cooling angle, the third wall is better. The results also show that although the third and fourth piers are different in terms of the distance of holes, the arrangement of the holes in the third wall is such that it has been able to cover the area between the cooling holes of the fourth stage in the beta = 0.

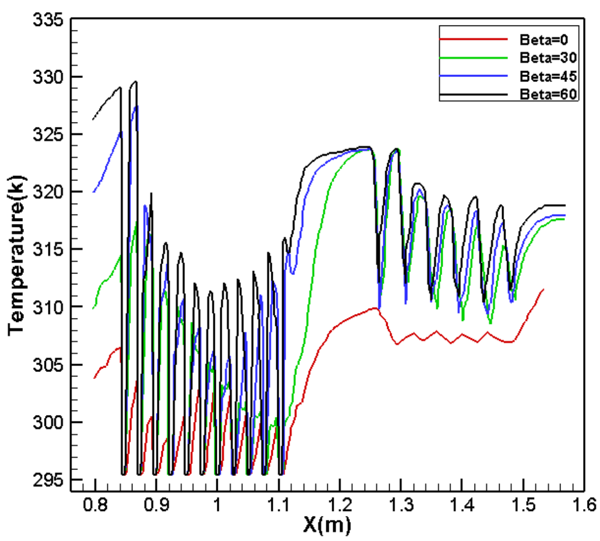

Fig. 18 The third and forth wall temperature graphs along the Z2 line.

In "Fig. 19" The temperature chart is shown along the Z3 line. This line passes through the holes in the third and fourth walls. The results show that Beta = 0 has a better cooling effect and increases with the lateral angle of the wall temperature.

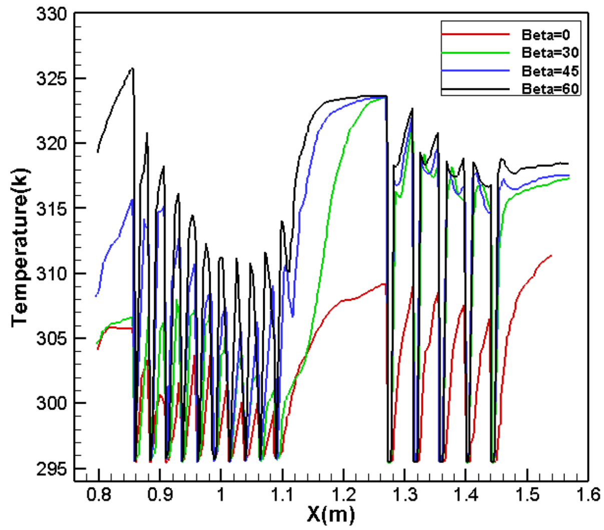

Fig. 19 The third and forth wall temperature graphs along the Z3.

The cooling effectiveness (h) is used to characterize the performance of film cooling. The h is defined as:

$$\eta=\frac{T_m-T_{aw}}{T_m-T_c}$$

Where Tm is the combustion gas temperature near combustor liner. Tc and Taw are the temperature of the coolant and the temperature of the wall, respectively.

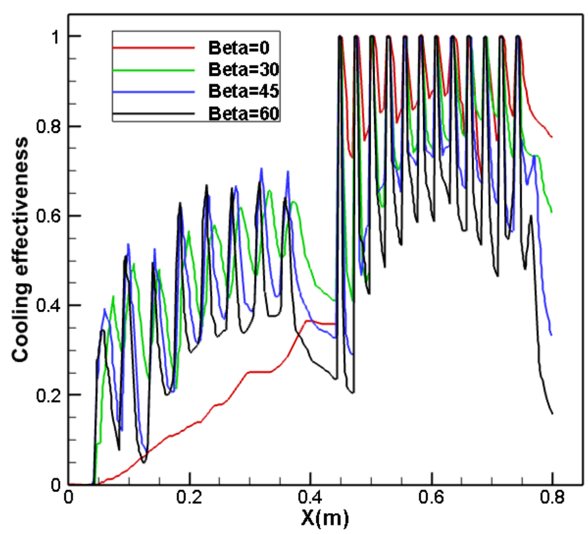

Fig. 20 The first and second cooling effectiveness graphs along the Z2.

The effect of cooling in direction of Z2 are shown in the “Fig. 20 and Fig. 21”. As it is clear, this line for the first and forth plates passes through the distance between the cooling holes but in the second and third plates it passes through the holes. In the first plate, the angle of compound increased averagely and has much differences with the condition of Beta=0. But on the third wall and with the increasing of the compound angle, the effect of cooling effectiveness decreases and this is because of high current.

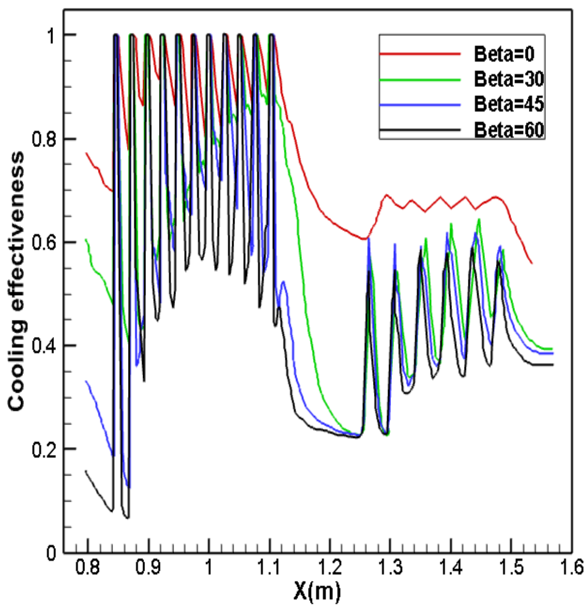

Fig. 21 The third and forth cooling effectiveness graphs along the Z2 line.

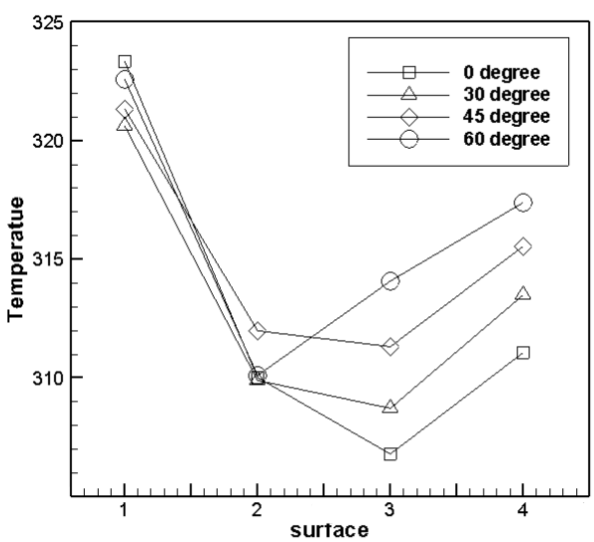

Fig. 22 Average tempratures in four walls.

In “Fig. 22”, the average temperature is four walls of the enclosure. In all walls, the average temperature of the walls is first reduced and then increased. The third wall except in Beta = 60, has the lowest temperature between the four walls. The average temperature at Beta = 0.60 from Beta = 45, 30 is higher for the first wall and the lowest temperature at the Beta angle is 30 and the highest temperature is similar to Beta=0 and less than Beta = 45. The results show that in the flat wall, the lowest average temperature in the Beta state is 30. In the third and fourth walls, the wall is sloping and has different results from the flat wall. The results show that with the increase in the lateral angle, the temperature of the median wall increases, and this is due to the hot flow that penetrates to the left.

7 CONCLUSION

In this study, the effect of cooling with compound angle was investigated on the wall temperature of the chamber. The simulated enclosure has two flat and two sloping walls, the layout of their cooling holes varies. The results show that the first and second flat walls in Beta=0 have a lower temperature than the cooled cooling mode along the cooling holes. However, in the area between the holes, it has the highest temperature and there is not much coolness in this area. In addition, in a cooling flat plate with compound angle, it can cover more area due to the air flows through the wall surface, so that the first and second walls have the lowest average temperature in a cooling compound angle. The third and fourth walls are sloping and different results for these walls were obtained from the first and second walls. The results showed that the minimum average temperature in this wall is Beta=0 and increases with the increase of the lateral side of the average temperature of the walls. In addition, the results showed that the walls with holes with a large number of holes and a distance less than the holes are slightly spaced apart before the walls with fewer holes and more distance of holes, in addition to reducing the temperature of the first wall, it can cover the distance between the holes in the second wall. Ultimately, the cooling of both walls is done well.

REFERENCES

[1] Lefebvre, Arthur, H., Gas Turbine Combustion, 3rd ed. CRC press, New York, 2010.

[2] Atul, K., Bogard, D. G., Adiabatic Effectiveness, Thermal Fields, and Velocity Fields for Film Cooling with Large Angle Injection, Journal of Turbomachinery, Vol. 119, No. 2, 1997, pp. 352-358.

[3] Foster, N. W., Lampard, D., The Flow and Film Cooling Effectiveness Following Injection through a Row of

Holes, Journal of Engineering for Power, Vol. 102, No. 3, 1980, pp. 584-588.

[4] Xiao, L., Zheng, H., Influence of Deflection Hole Angle on Effusion Cooling in a Real Combustion Chamber Condition, Thermal Science, Vol. 19, No. 2, 2015, pp. 645-656.

[5] Koc, I., Parmaksızoglu, C., and Cakan, M., Numerical Investigation of Film Cooling Effectiveness on the Curved Surface, Energy Conversion and Management, Vol. 47, No. 9-10, 2006, pp. 1231-1246.

[6] Goldstein, R. J., Jin, P., Film Cooling Downstream of a Row of Discrete Holes with Compound Angle, Journal of Turbomachinery, Vol. 123 No. 2, 2001, pp. 222-230.

[7] Gustafsson, K. M., Johansson, T. G., An Experimental Study of Surface Temperature Distribution on Effusion-Cooled Plates, Journal of Engineering for Gas Turbines and Power, Vol. 123, No. 2, 2001, pp. 308-316.

[8] Hay, N., Lampard, D., and Saluja, C. L., Effects of Cooling Films on the Heat Transfer Coefficient on a Flat Plate with Zero Mainstream Pressure Gradient, Journal of Engineering for Gas Turbines and Power, Vol. 107, No. 1, 1985, pp. 105-110.

[9] Ammari, H. D., Hay, N., and Lampard, D., The Effect of Density Ratio on the Heat Transfer Coefficient from a Film-Cooled Flat Plate, Journal of Turbomachinery, Vol. 112, No. 3, 1990, pp. 444-450.

[10] Hale, C. A., Plesniak, M. W., and Ramadhyani, S., Film Cooling Effectiveness for Short Film Cooling Holes Fed by a Narrow Plenum, Journal of Turbomachinery, Vol. 122, No. 3, 2000, pp. 553-557.

[11] Maiteh, B. Y., Jubran, B. A., Effect of Pressure Gradient on Film Cooling Effectiveness from Two Rows of Simple and Compound angle holes in combination, Energy Conversion and Management, Vol. 45, No. 9-10, 2004, pp. 1457-1469.

[12] Jubran, B., Brown, A., Film Cooling from Two Rows of Holes Inclined in the Streamwise and Spanwise Directions, Journal of Engineering for Gas Turbines and Power, Vol. 107, No. 1 1985, pp. 84-91.

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

[14] Schmidt, D. L., Sen, B., and Bogard, D. G., Film Cooling with Compound Angle Holes: Adiabatic Effectiveness, Journal of Turbomachinery, Vol. 118, No. 4 1996, pp. 807-813.

[15] Baldauf, S. A., Scheurlen, M., Schulz, A., and Wittig, S., Correlation of Film Cooling Effectiveness from Thermographic Measurements at Engine Like Conditions, ASME Turbo Expo 2002: Power for Land, Sea, and Air, pp. 149-162. American Society of Mechanical Engineers, 2002.

[16] Vakil, Suresh, S., and Thole, K. A., Flow and Thermal Field Measurements in a Combustor Simulator Relevant to a Gas Turbine Aero-Engine", ASME Turbo Expo 2003, Collocated with the 2003 International Joint Power Generation Conference, American Society of Mechanical Engineers, 2003, pp. 215-224.

[17] E. Kianpour, Nor Azwadi, E., Sidik, C. S., and Agha Seyyed Mirza Bozorg, M., Thermodynamic Analysis of Flow Field at the end of Combustor Simulator, International Journal of Heat and Mass Transfer, Vol. 61, 2013, 389-396.