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Investigation of matrix fin based effluent cooling system

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Abstract. The aviation market is expected to achieve a compound annual growth rate of 3% over the forecast period 2019 to 2024. The main objective of this project is to increase the cooling effectiveness of the transply effusion cooling system using matrix fins. The geometric parameters of the matrix fin are optimised using MATLAB and these are used to design the matrix fin within the effusion cooling system. The design of the effusion cooling system was taken from the standard designs which are currently in use. The cooling effectiveness of the matrix fin based transply effusion cooling system was calculated using the temperature values that are obtained from the analysis for different conditions of inlet and outlet fluid temperature. For hot gas inlet temperature 500K the average temperature of the cooling system was 356.011K. Similar analysis is conducted on the effusion cooling system without the matrix fin design with inlet fluid temperature 500K the average temperature of the cooling system was 384.966K. To see the effect of increase in the temperature of the combustion chamber the hot fluid inlet temperature is increased to 850K the average temperature of cooling system was357.612K. The outcome of the analysis was that the cooling system with the matrix fins had better cooling effectiveness than the cooling system without the matrix fins.

1. Introduction

Temperature of the combustion chamber of the modern jet engine can reach as high as 2000K which is too high for most engineering materials [1]. Many methods are used to cool the combustion liner machined cooling ring [2], corrugated strip cooling, splash cooling strip, transpiration cooling [3]. Effusion cooling is regarded as a more effective cooling scheme for protecting the combustion liner of the jet engines [4-7].Andrews et al, studied the effects of main geometric and aero-thermal factors on the thermal and aerodynamic performances of an effusion cooling scheme.[8, 9]. Bohn and Moritz[10], Scrittore et al. [11] , and Yang and Zhang [12,13] investigated numerically or experimentally the developing process of coolant jets injected from effusion holes.. A lot of researchers have been focusing on promoting the internal cooling performance [14].
An intensive experimental survey was performed to study the heat transfer and friction performance of different matrix cooling geometries in view of a possible application as internal cooling systems of both nozzles and vanes of industrial gas turbines [15].This activity has been carried out within collaboration between the Department of Industrial Engineering of the University of Florence and GE Oil & Gas [16].

Among the Gas Turbine manufacturers form the western world, the matrix fins system is relatively unknown. This is because the application of the matrix structures as cooling systems in gas turbine air foils originates from former Soviet design engineering system and were largely unknown until the recent dissolution of the Soviet Union in the 1980's, at which time Russian research works began to appear in the international literature. The use of the matrix fin in the transply effusion cooling system to increase the cooling effectiveness of the combustion liner is done by observing the studies that are conducted on the gas turbine cooling system has inspired us to apply the matrix fin cooling system with the existing transply effusion cooling system.

2. Optimisation of Fin arrays

The idea of applying the matrix fin in the effusion cooling system might increase the cooling effectiveness but we need the optimized geometric parameters like height, thickness and the spacing between fin arrays so that we have maximum heat transfer from the matrix fin. Convection heat transfer is the product of the convection coefficient and total surface area for constant temperature difference between fin surface and surrounding. Heat transfer can be increased by increasing either one of them or both of them but increasing the surface area further has negative effect on the Nusselt number. Increasing the number of fins increases the surface area but it does not necessarily increase the convection heat transfer it is because of the reduction in the convection coefficient due to the negative effect on the Nusselt number. In the **Figure 1** we can see the variation of the heat transfer for the velocity of the fluid 20m/s and the same variation can be seen in the **Figure 2** where the analysis is done for the velocity of the fluid 60m/s. The graphs show that there is no change in the positions of the points due to the change in the velocity; instead the whole graph is lifted upwards due to increase in the velocity of the fluid which in turns increases the convective heat transfer

The final optimized parameters of the matrix fin have been obtained from the MATLAB simulations and the dimensions of the hole diameter and their arrangement was taken from the research papers using these geometric parameters solid model is designed in the Solid Works 2016. Top view and corner view of the optimized part are as shown in **Figure 3** and **Figure 4**, respectively.

Table 1 Dimensions used for the designing of the model.

Serial number	Parameter	Value
1	Fin Height	0.7mm
2	Fin Thickness	0.5mm
3	Distance Between Fins	0.865mm
4	Hole Diameter	0.5mm
5	Streamwise Pitch	1.03mm
6	Spanwise Pitch	0.91mm
7	Thickness of Effusion Plate	0.5mm

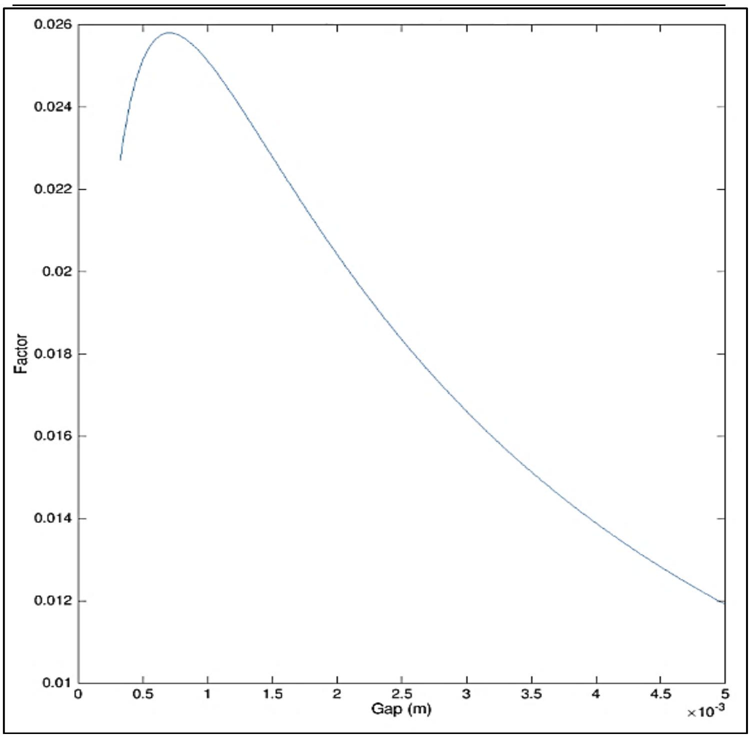

Figure 1. Convection heat transfer variation for fin thickness 5mm, spacing 0.865mm, and velocity 20 m/s.

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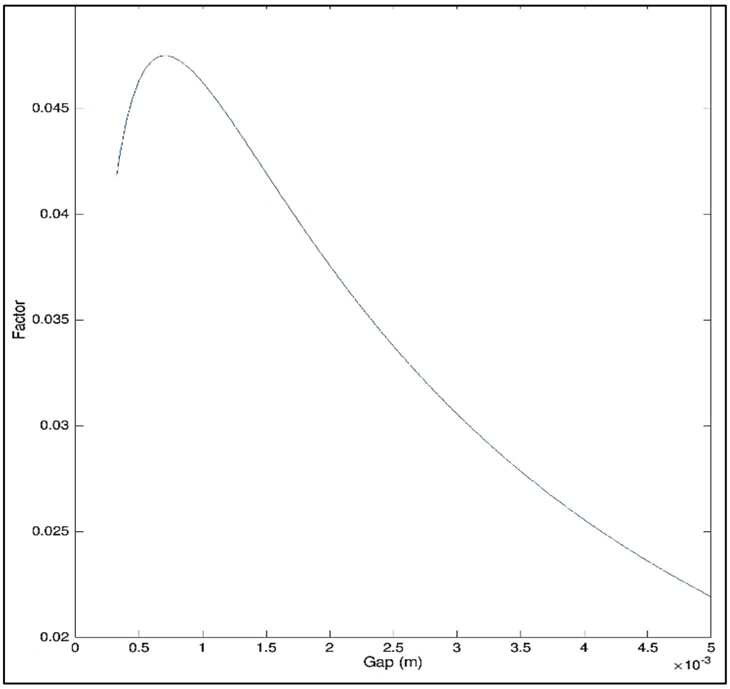

Figure 2. Convection heat transfer variation for fin thickness 5mm, spacing 0.865mm, and velocity 60 m/s.

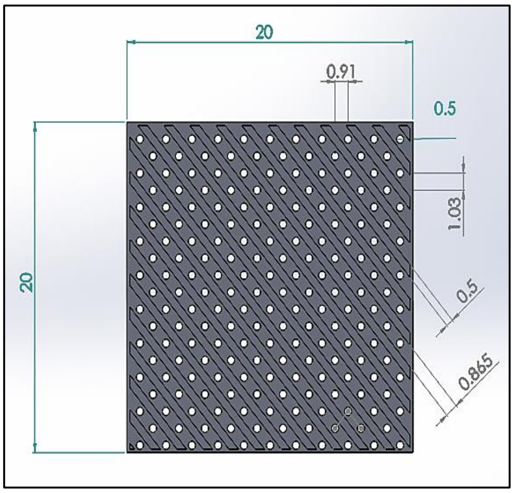

Figure 3. Top view of the optimised part.

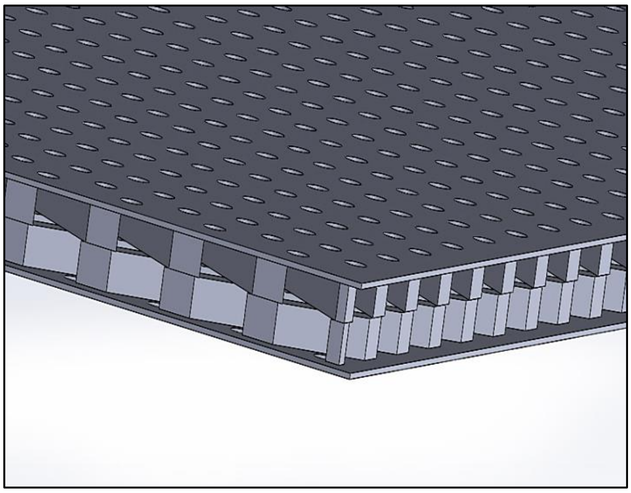

Figure 4. Corner view of the final optimized part.

3. Numerical Analysis

The optimised model of matrix fin effusion cooling system was designed in the Solid Works 2016is imported in to the ANSYS Fluent geometry. Two inlets are used to simulate the annular air and the fluid present in the combustion chamber. Inlet velocity of the hot fluid 11.3m/s with temperature 500K is used as hot fluid inlet boundary condition and for cold fluid 20m/s velocity with temperature 300K is used as cold fluid inlet boundary condition.

3.1. For Hot Gas Inlet Temperature 500K

Cooling From the analysis we are able to obtain the temperature profile and get the average value of the temperature of the model, the obtained temperature is then used to calculate the cooling effectiveness using the formula,

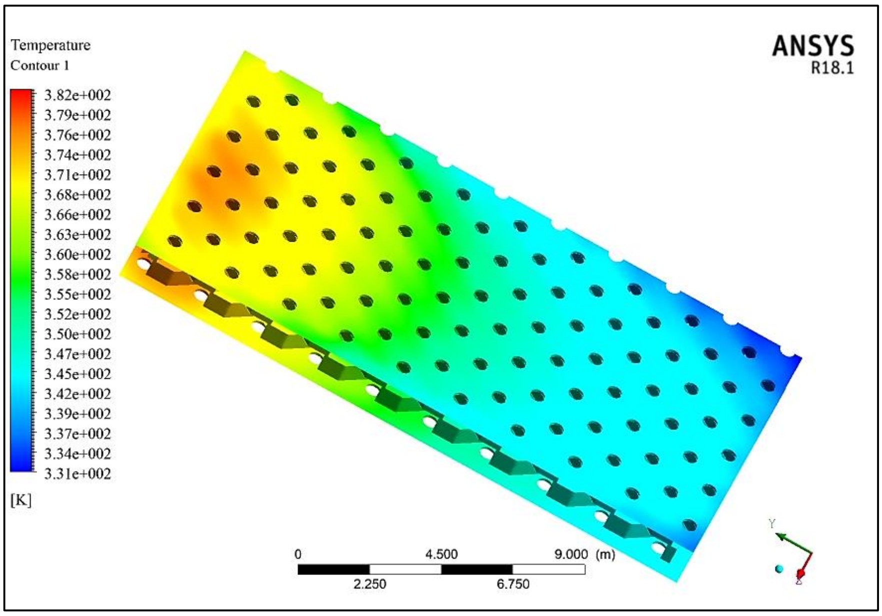

Figure 5. Temperature profile of the model.

Effectiveness = $(T_G - T_W)/(T_G - T_C)$

Where T_G is hot fluid temperature

T_W is wall temperature

T_C is cold fluid temperature

Average temperature = 356.011 K

Maximum temperature = 383.315 K

Minimum temperature = 331.22 K

Cooling effectiveness $= (500 - 356.011)/(500 - 300)$

= 0.7199

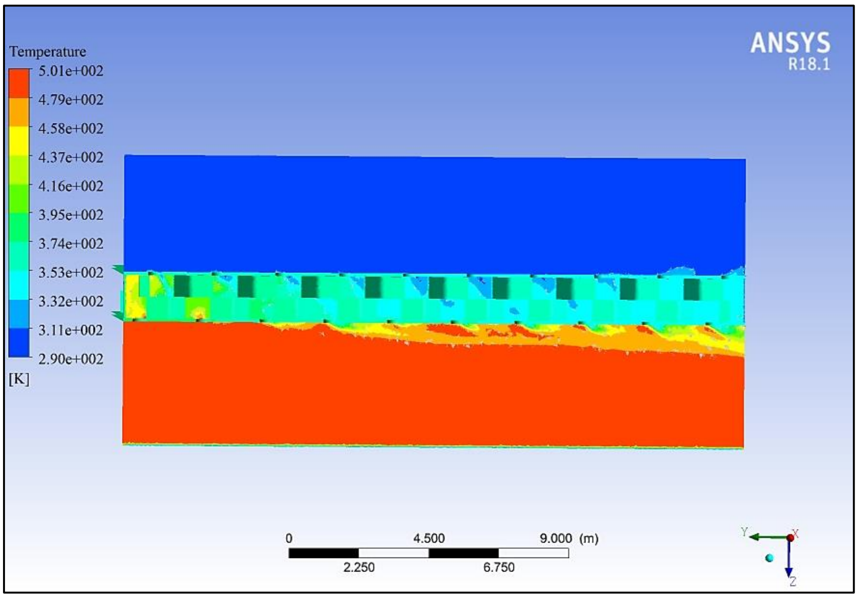

Figure 6. Boundary layer formation.

3.2. *For Hot Gas Inlet temperature 500K, model without the matrix fin*

The same analysis is conducted on the model without matrix fin in effusion cooling system and from the analysis we saw that the temperature of the effusion cooling system is more compared to the effusion cooling system with matrix fin the temperature profile of the model can be seen in the **Figure 7**, and the cooling effectiveness is less. The boundary layer formation can be seen in the **Figure 8.**

From the analysis we are able to obtain the temperature profile and get the average value of the temperature of the model; the obtained temperature is then used to calculate the cooling effectiveness using the formula

Average temperature = 384.966 K
Maximum temperature = 425.135 K
Minimum temperature = 334.105 K
Cooling effectiveness = $(500 - 384.966)/(500 - 300)$ = 0.5752

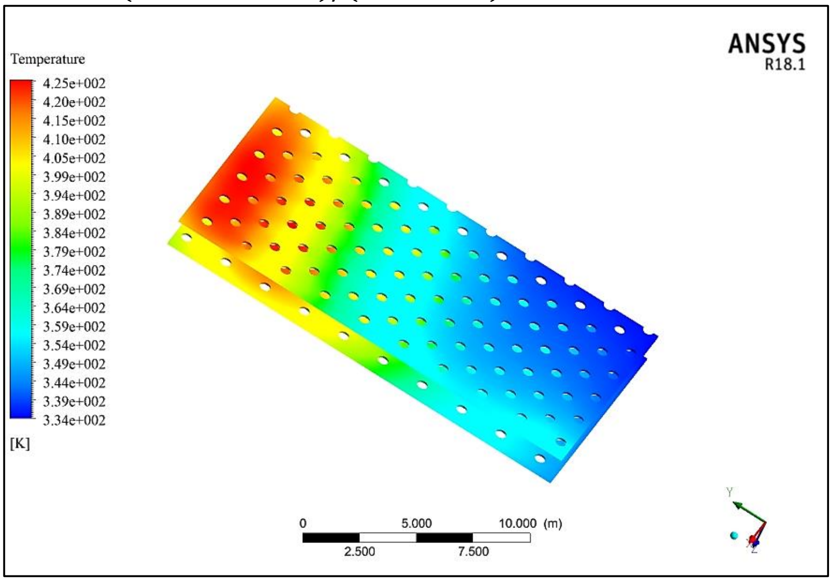

Figure 7. Temperature profile of the model.

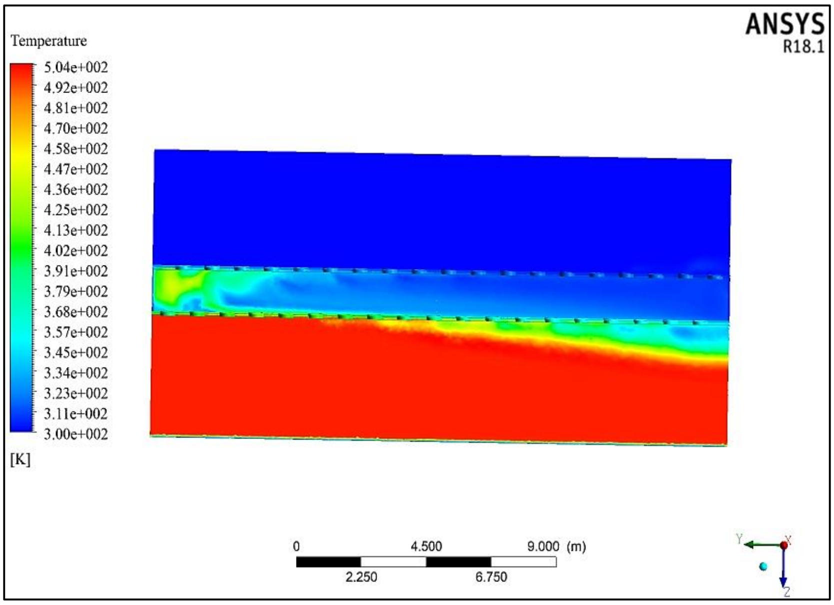

Figure 8. Boundary layer formation.

3.3. *For hot fluid temperature 850K*

To see the effect of the temperature of hot fluid we did the analysis on the model with matrix fin using the hot fluid temperature as 850K, and the other boundary conditions are kept same. Since the temperature is varying along the length of the model average temperature of the model is used to calculate the cooling effectiveness. Using the functional calculator, we are able to get the maximum temperature equal to417.14K, minimum temperature equal to 319.829K, and average temperature equal to357.612K. We can see form the analysis that the maximum temperature is 417.14K that is way below the temperature of the hot combustion environment this is due to the formation of the boundary layer of the cold fluid on the solid surface which is facing the combustion zone. These boundary formations can be seen in the **Figure 9** where the cold fluid enters through the effusion holes from the top and pass through the matrix fin and forms the cold fluid boundary layer on the hot side of the plate such that it prevents the hot fluid of the combustion coming in direct contact with the combustion liner.

From the analysis we are able to obtain the temperature profile and get the average value of the temperature of the model; the obtained temperature is then used to calculate the cooling effectiveness using the formula

Average temperature = 357.612K
Maximum temperature = 417.14 K
Minimum temperature = 319.829 K
Cooling effectiveness $= (850 - 357.612)/(850 - 300)$
$= 0.8952$

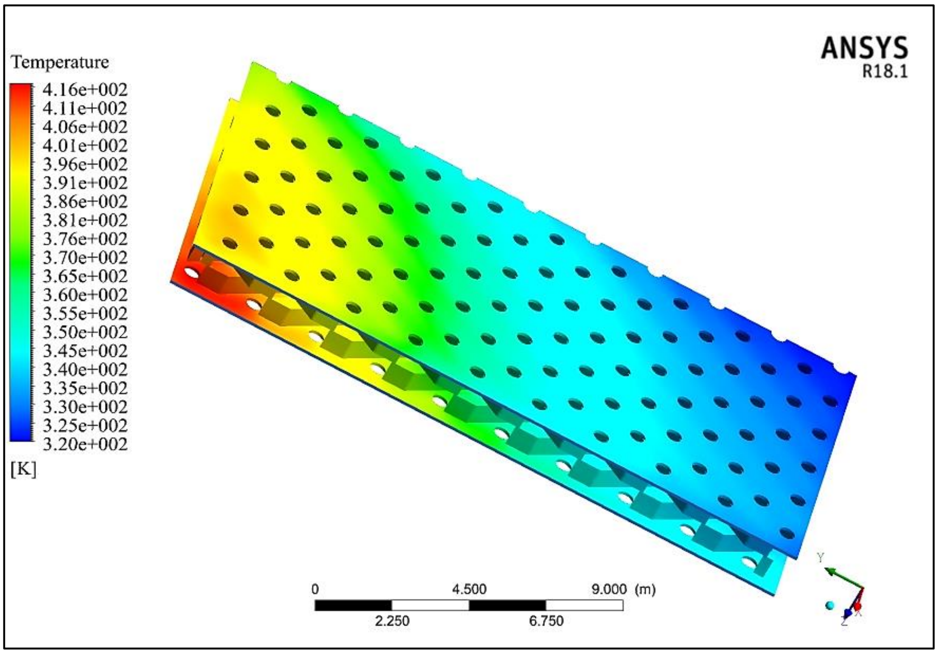

Figure 9. Temperature profile of the model.

4. Conclusion

There are multiple parameters whose values influence the performance of the matrix fins. To find the optimisation combination of the parametric values, it is important to use the proper mathematical models which are applicable for the desired operating conditions. MATLAB is used to obtain the optimum parameters of the fin geometry, and the graphs have shown that the change in the velocity of the fluid has no effect on the optimum point. Design of the model is done using these parameters and analysis is done using ANSYS proving that the new matrix fin transply effusion cooling to be more effective than the current transply effusion cooling system. An increase in cooling effectiveness by 14.47% for hot fluid temperature of 500K and 32% for hot fluid temperature of 850K (keeping cold fluid temperature at a constant value of 300K) was obtained by applying the matrix fin in to the effusion cooling system which is a significant improvement. Furthermore, when the combustion chamber temperature increased from 500K to 850K, there was only a 1.6K rise in the average temperature of the wall which implies that it is possible to increase the temperature of the combustion chamber above the metallurgical limitations.

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