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Research Paper

NUMERICAL INVESTIGATION OF FLOW AND TEMPERATURE CHARACTERISTICS ENHANCEMENT IN TUBOANNULAR COMBUSTOR

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This paper is concerned with the improving the cooling effectiveness of the tuboannular combustor. The first approach of this project is to design the tuboannular combustor and then carrying out the thermo-fluid analysis. Combustion process is complex phenomena the design optimization process requires a large number of analysis where experimental method will be complex and time consuming thus Ccomputational Fluid Dynamics (CFD) simulations are often used to predict and visualize the complex combustion process. In this project CFD tool utilized is Ansys Fluent where flow analysis is conducted on the optimized model. The combustor model is designed in SolidWorks 15. The combustor design is optimized by varying the cooling holes diameter and orientation. The obtained results data were studied and came up with an efficient cooling combustor.

Keywords: CFD, Combustor, Combustor cooling, Effusion cooling, Film cooling, Flow analysis, Gas turbine engine, Heat transfer, Thermal analysis

INTRODUCTION

Combustion process is a complex phenomenon involving principals of fluid mechanics, thermodynamics and chemical reactions. Combustion intake air temperature already reaches to 200-550 °C (Arthur Lefebvre and Dilip Ballal, 2010) due to work done during compression. The combustion process rises this temperature by 650-1150 °C to maintain the temperature range of 900-1800 °C. But combustion temperature and temperature required at turbine varies with engine thrust required.

Increase in compressor pressure ratio and turbine inlet temperature enhances thermal efficiency of a gas turbine but it induces the thermal stress in the combustion chamber. So the need for effective cooling becomes more and more vivid. About 20% (Arthur Lefebvre and Dilip Ballal, 2010) of air leaving compressor enters combustor through swirler and participate in

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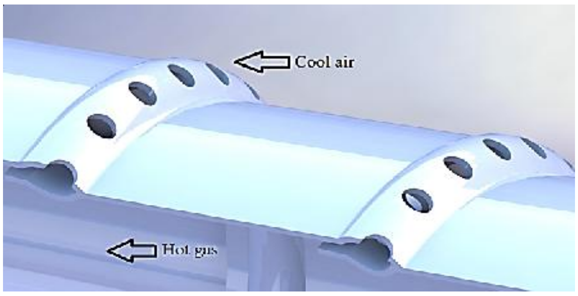
combustion whereas rest 80% is deployed for cooling process by different cooling methods. The combustion chamber is provided with outer casing and inner liner where the hot gases flow. The cooled air drawn from compressor separates them. Higher pressure ratio in compressor increases heat transfer to the liner wall by the radiation because combustion inlet temperature will be high and air to cool the wall by convection will also be at higher temperature.

Therefore, following cooling methods have been associated in combustor to enhance overall combustion efficiency.

Film Cooling

Film cooling method includes number of cooling slots in liner wall to allow thin layer of cooling air (compressed air). The cooling slot can be designed to withstand severe pressure and thermal stress at high temperature for longer duration which is the main advantage of this method.

Figure 1: Film Cooling

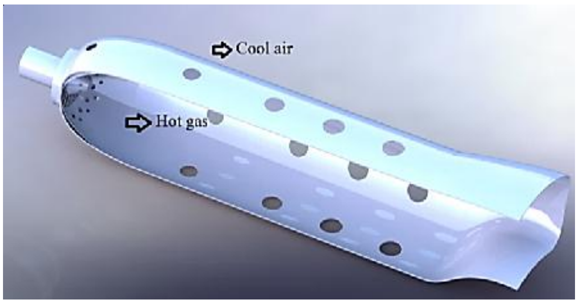


Multi-Holed Wall (Effusion Cooling)

Multi-holed walls are very effective way to lower the amount of air needed for cooling.

The effectiveness is due to increase in convection inside the holes. By optimizing the geometry of combustion chamber, air velocity and efficient cooling of hot gases can be achieved with this method with minimum mass flow rate of air.

Figure 2: Multi-Holed Wall



The development and advancement in the gas turbine engine has led to various researches in combustor model. To ensure a satisfactory liner life, it is important to keep temperatures and temperature gradients down to an acceptable level were described by Arthur Lefebvre and Dilip Ballal (2010). Various approaches have been made to study combustion chamber and applicability of cooling methods in it.1-D empirical design of the combustion chamber was carried out by Johannes Jacobus Gows (2007). With his design he made the temperature and velocity profile predictions inside the combustor. He showed up the heat transfer process inside the chamber giving the probable thermal equations for different points inside the combustor.

The wall temperature and the cooling effectiveness of deflection hole on effusion cooling were analyzed by Xiao Liu and Hongtao Zheng (2015), to investigate the effusion cooling performance in real combustion chamber with strong rotation and primary holes provided. Effusion cooling performance was found better than the conventional film cooling methods. With deflection hole on effusion cooling, the wall temperature, gradient was lowered by significant value, the coolant was reduced by 20%, moreover, higher cooling efficiency was obtained. 60 degree deflection of cooling holes was found to be best suited for effective cooling.

The mechanics of film cooling was described by Eidon Knuth (1993). The effect of high turbulent gas streams on the thin liquid wall films of the combustor were studied by him. The methods for calculating maximum allowable coolant flow rate for stable coolant film, determining the evaporation rate and the surface temperature for stable inert coolant film was found.

DESIGN AND ANALYSIS

Geometric Model

The model designed here is the tuboannular type combustor. As carrying out the analysis of the whole tuboannular combustor is complex and time consuming, thus single can combustor is used to conduct the analysis. The CAD design is made in SolidWorks 2015 and CFD analysis was carried out in Ansys Workbench 15.

Boundary Conditions

- Solver: Pressure based steady state
- Viscous Model: Standard k-e, Standard wall function
- Radiation Model-P1
- Air Inlet Velocity: 140 m/s (M = 0.4) Temperature: 550 K
- Fuel Inlet Velocity: 8 m/s
- Outlet: Pressure constant
- Wall

  Motion - Stationary

  Shear Condition - No Slip

  Material Used: Nimonic - 75

  Fuel species used: Jet A gas

RESULTS

Flow Analysis

The flow analysis was carried out with the model show in Figure 3. Ansys Fluent is used to conduct the flow analysis.

Velocity Profile

The velocity is minimum about 70 m/s primary zone (Figure 4) because of swirling effect. Once the combustion takes place, velocity increases along the length of chamber with approx. 500 m/s at dilution zone and approx. 650 m/s at outlet.

High velocity (approx. 850 m/s) region is formed at the centre of nozzle guide vane.

Temperature Profile

Flame is observed to get stabilized well within the primary zone. Combustion temperature at

Figure 3: Can Combustor

Figure 4: Velocity Contour

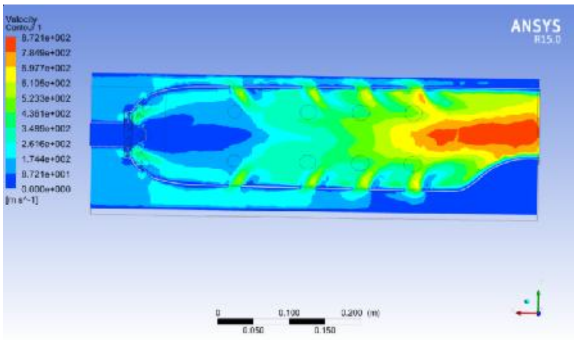
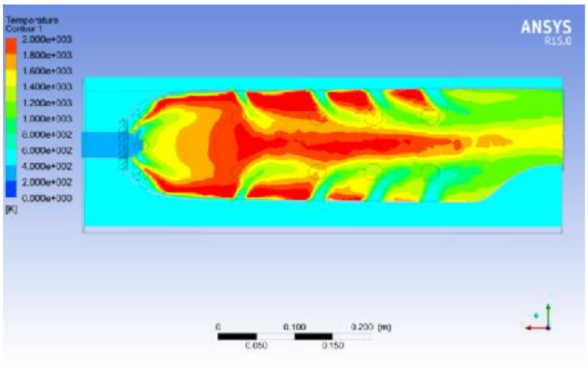


Figure 5: Temperature Contour



Primary zone is about 1900 K (Figure 5), temperature increases towards the wall reaching maximum temperature of about 2000 K near the wall of primary and intermediate zone (Figure 5). Flame propagates axially along the length of flame tube with temperature approx. 1900 K (Figure 5).

Cooling holes in dilution zone consequently cools the flame temperature. The outlet temperature is approx. 1100 K near the walls (Figure 5), but small region at the centre with temperature approx. 1600K is formed.

Limitation

- Patches of high velocity region (approx. 850 m/s) in outlet impart high surface stress.
- Higher temperature profile on the combustor wall produce higher thermal stress.

In order to overcome the limitations of above design, optimization is carried out by introducing series of film cooling and varying the multi holed cooling slots.

Figure 6: Optimized Model

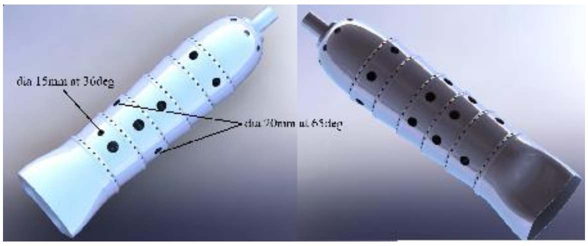
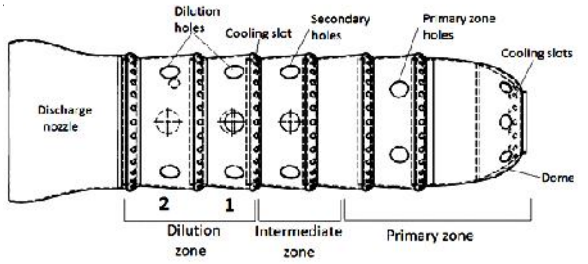


Figure 7: Details of Optimized Model



Optimized Model

The Figure 7 shows the 2D geometry of the optimized combustor model indicating different combustor section.

The number of cooling holes in each section is as follows:

Primary Zone: 6 holes

Secondary Holes: 4 holes

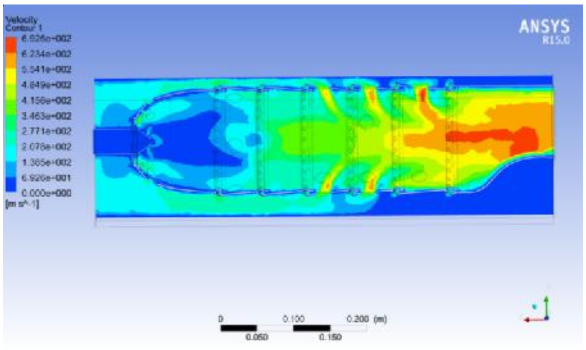
Dilution Zone (Section 1): 4 holes

(Section 2): 5 holes

Velocity Profile

The velocity is minimum about 70 m/s primary zone (Figure 8) because of swirling effect. Once the combustion takes place, velocity increases along the length of chamber with approx. 500 m/s

Figure 8: Velocity Contour



at dilution zone and approx. 650 m/s at outlet. Size of high velocity (approx. 800 m/s) region formed near end of dilution zone reduced to tiny as compared to 1st model.

Temperature Profile

Combustion temperature at Primary zone is about 2200 K (Figure 9); same temperature reaches near the chamber wall of intermediate zone. Cooling holes in dilution zone consequently cools the flame temperature and introduction of 15 mm diameter hole in this zone produced significant cooling effect which lowers the temperature to 1800 K.

The outlet temperature is approx. 1100 K near the top walls, but approx. 950 K at bottom with high temperature region of 1180 K on left top corner (Figure 12).

Figure 9: Temperature Contour (Top) and Primary Zone (Bottom)

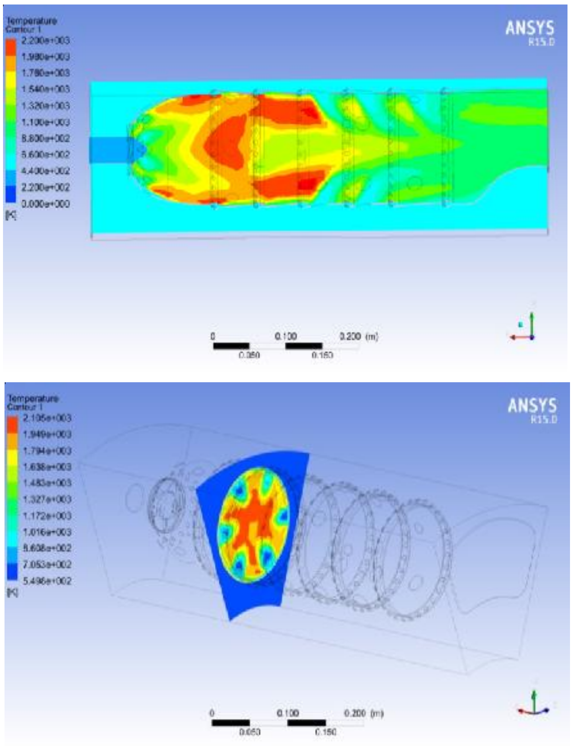


Figure 10: Intermediate Zone

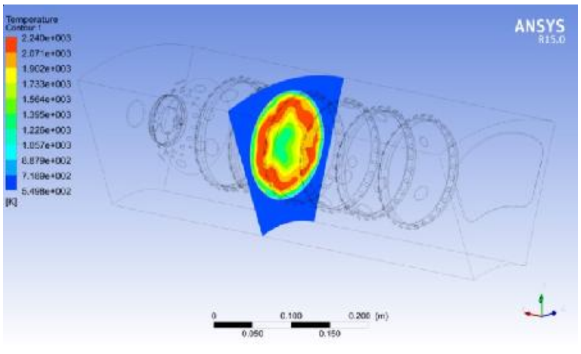
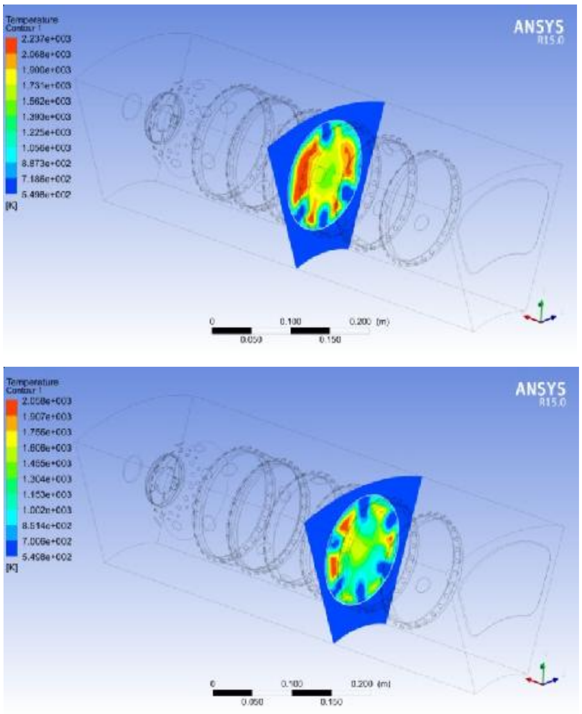


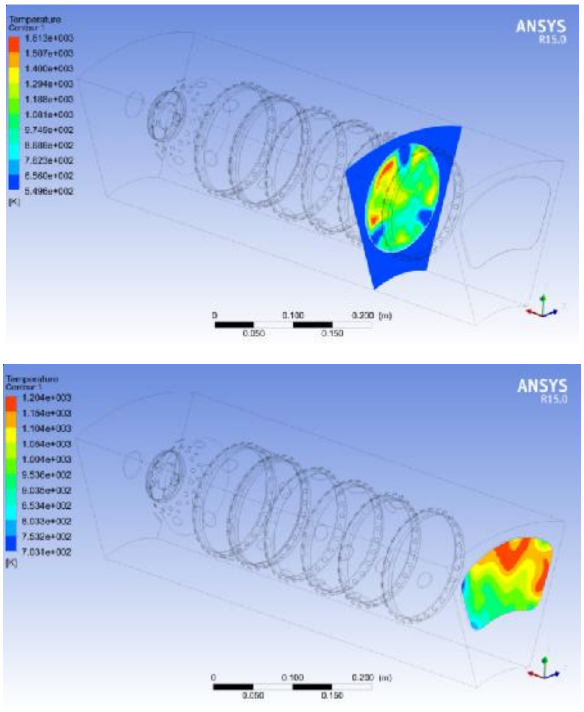
Figure 11: Secondary Holes (Top) and Dilution Zone Section 1 (Bottom)



Thermal Analysis

The material used in combustor is Nimonic 75, where the maximum operating temperature should not exceed 1350 °C. Temperature of the gases released by the combustion process may peak over 2000 °C; this is much higher than the melting point of the combustor flame tube and turbine blades. Therefore there should be

Figure 12: Dilution Zone Section 2 (Top) and Outlet Temperature (Bottom)



sufficient cooling to all the metal surfaces exposed to the hot gases to improve structural integrity and durability.

From Figure 13 we can see that, there is proper cooling in intermediate and dilution zone. Due to film cooling the body temperature in intermediate and dilution zone is below the melting point. Where as in primary zone the body temperature is reaching above 2000 K, which is above the melting point of the metal. Thus the region in primary zone needs to be cooled.

Figure 13: Surface Temperature of First Combustor

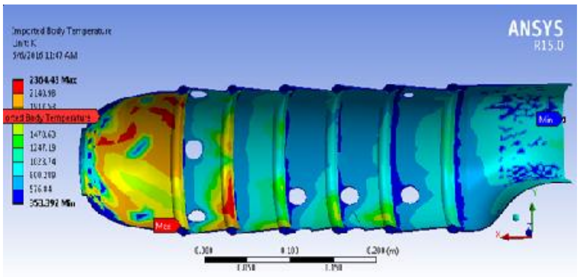


Figure 14: The Model with Film Cooling in Primary Zone

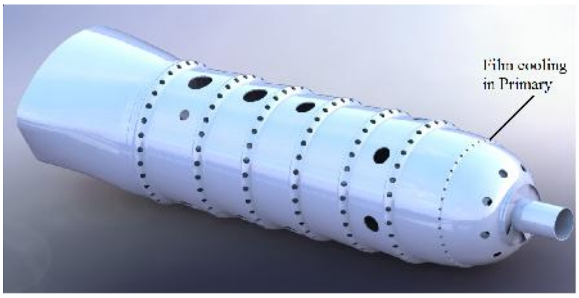
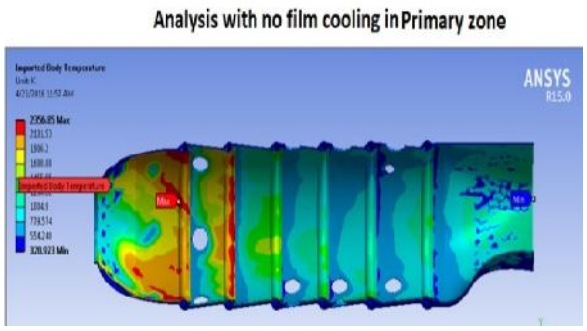


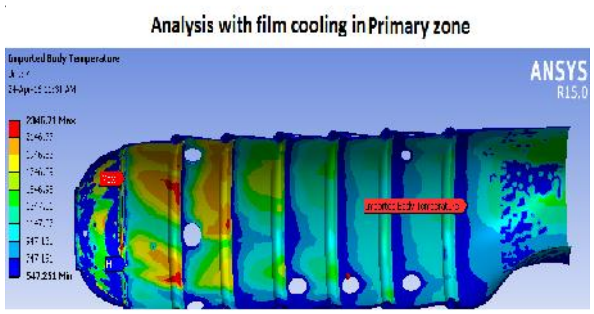
Figure 15: Without Film Cooling in Primary Zone



In observation, we noticed that the body temperature in primary zone of the optimized model is reaching higher temperature value of approx. 2300 K. As we know film cooling method is efficient to reduce the surface temperature of the body. So we have made the modification in the geometry of the optimized model by introducing film cooling layer in the primary zone.

After making the changes in the model, flow and thermal analysis were carried out. In thermal analysis we noticed that after introducing additional film cooling in the primary zone there was significant change in the body temperature (Figure 16). The average surface temperature in the primary zone reduces from 2200 K to 1400 K

Figure 16: Model with Film Cooling in Primary Zone



(approx.) (Figure 16). Lowering the temperature of the primary zone by introduction of film cooling can reduce venerability of damaging the combustor wall and corrosion.

Figure 15 shows the thermal analysis result of optimized model and Figure 16 shows the model with film cooling in primary zone. By comparing two we notice that after introducing film cooling the body temperature in prima-ry zone has reduce to optimum level.

CONCLUSION

We made the approach to design the combustor model and optimize it by varying the cooling slots. Thermo-Fluid analysis of the combustion chamber is carried out using the CFD software Ansys. First combustor model is designed with multi-holed; the analysis shows higher impact stress toward outlet wall with thermal stress in primary zone and the dilution zone of the combustor. These limitations were overcome by optimizing design, introducing film cooling and varying multi holed orientations.

With optimized design, proper outlet velocity of 650 m/s, complete or proper combustion and flame stabilization in primary zone, efficient temperature profile and optimum outlet temperature range of 950-1100 K was obtained which is capable of enhancing the overall combustion efficiency.

Moreover additional film cooling in the primary zone of optimized combustor was able to lower the surface temperature to the optimum value. So, to avoid higher surface temperature inside the combustion chamber, these kinds of film cooling layer can be added.

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