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STUDY ON THERMOSTRUCTURAL BEHAVIOUR OF LIQUID OXYGEN IN AIRCRAFT TURBINE FUEL ENGINE

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Abstract

The most common problem in the design of rocket engine components is the high temperatures and the high pressures which it is subjected to. This can result in critical failure of components like explosive blasts. Hence the structural integrity of the rocket engine part is of utmost importance in their design. In order to perform well at high temperature Inconel 718 is considered because of its excellent mechanical strength at high temperatures. But the mass of the components should not be increased to improve the strength of the component. It is essential for rocket engine parts to have less mass and at the same time have sufficient load carrying capacity. The objective of this work is to study the thermo structural behavior of injector plate of LOX/ATF engine. In this study, 3D CAD model of the injector plate including the channels and the injector elements is created using modeling software and finite element analysis is carried out to investigate the thermo structural behavior of the injector plate. The thermal stresses and deformation which is obtained is further minimized to arrive at a reduced mass. Conjugate Heat Transfer (CHT) method and Coupled Field Analysis is used to obtain the thermal stresses and deformation. A Response Surface Method (RSM) is used as a statistical method to perform the mass optimization of the design.

Keywords: Fuel, Rocket Engine, Computational Fluid Dynamics, Structural Analysis, FEA

1. Introduction

Generally a rocket engine consists of injector plate, thrust chamber, nozzle and igniter and other essential accessories. The main function of the rocket engine is to produce a thrust which can lift the whole mass of the rocket. The thrust is produced by combustion of a fuel and oxidiser in the combustion chamber. This fuel and oxidiser is injected into the combustion chamber in the form of spray droplets with the help of injector plate. The injector plate carries the fuel and oxidizer through internal channels and supplies it to the combustion chamber where combustion takes place. In order to withstand the combustion temperature, combustion pressure and the temperature and pressure in the fuel and oxidiser channels, the injector plate material and geometry should have sufficient strength to withstand the thermostructural stresses. The design of the injector plate which is structurally strong also increases the mass of the injector plate. This increase in mass affects the load carrying capacity of the rocket. Hence an injector plate has to be optimised for reduced mass and improved structural strength. Computational Fluid Dynamics (CFD) is used to perform Conjugate Heat Transfer analysis (CHT).

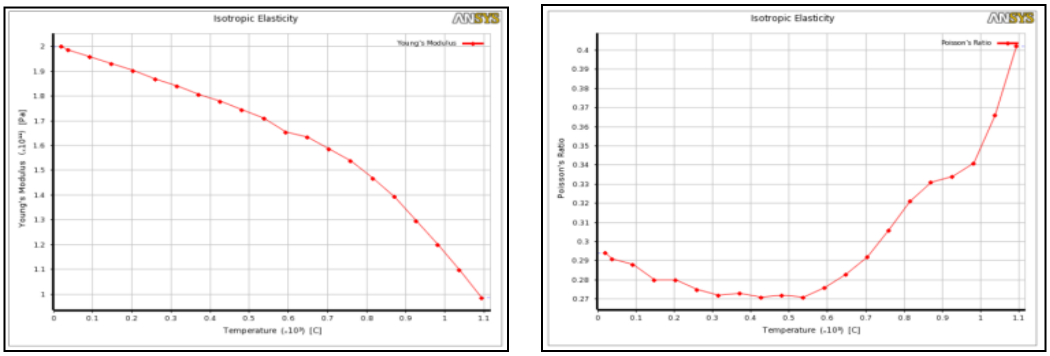
CFD works on the principle of Finite Volume Method (FVM). FVM discretises the fluid domain into a number of small domains. General conservation equations like mass, momentum, energy is solved on this set of control volume, which is then converted into algebraic equations for the ease of computation. Finite Element Method (FEM) is used to simulate the thermostructural analysis. FEM uses the concept of piecewise polynomial approximation, by dividing the continuum to a number of finite elements. Governing equations and boundary conditions are applied to each element, which is then converted into a set of algebraic equations. Jaiwen Song et al developed a 3D finite volume fluid-thermal-structural coupling methodology for analysis of thrust chamber walls and compared the results for linear and nonlinear material model. The comparison showed that the nonlinear model is better at predicting strains at the inner wall. An improvement in accuracy of 40% is obtained by using nonlinear model. Malgorzata Orlowska et al used a thermostructural numerical model to evaluate the stresses at the thrust chamber and nozzle walls. The analysis showed that the nozzle throat is subjected to high temperatures 1600oC and stresses of 1650 MPa and this is overcome by using graphite inserts at the throat.

Detlef Kehl et al made a coupled fluid structure interaction model to predict the thermostructural stresses in the European rocket engine named as Vulcain. The failure mechanism of the combustion chamber and the governing parameters are identified. Optimization method is developed to increase the life cycle of engine. The chamber wall thickness is reduced by 25% to improve the life cycle of the engine. Santhini et al determined that the thin walled construction of the rocket engine thrust chambers is better at reducing the temperature at the chamber walls and also withstanding the pressure produced. A chaboche nonlinear kinematic material model is being used to model the cycling behaviour of stress which varies between +60 MPa and -60 MPa. Daniele et al investigated on the cooling jackets which is essential in reducing the temperature of the rocket engine walls. The experimental method is developed using a subscale model of the rocket engine and observations were made that the cooling jackets play a significant role in cooling the high temperature walls, reducing the temperature by 100°C. Kang et al studied two methods, one using analytical equations and the other using computational fluid dynamics to find the temperature distribution of the engine due to heat transfer. Comparing the data with experimental hot fire test revealed that the computational fluid dynamics appears close to the experimental results with an error of only 1.41%.

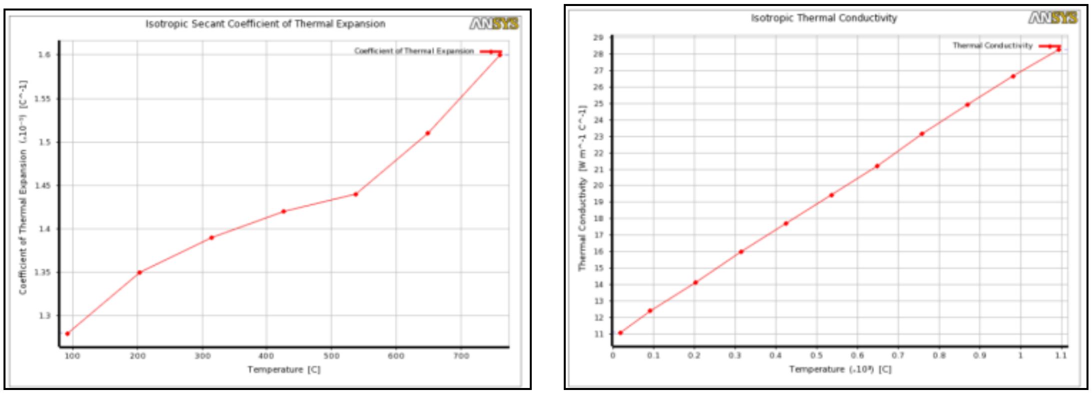
Ferraiuolo et al developed an integrated 2D model of thrust chamber and the injector plate. Analysis on different cases of cooling jacket arrangement showed that a counter flow cooling passage starting at the nozzle throat provides the most efficient cooling. This also increases the temperature of the oxidiser to 77oC which increases the combustion efficiency because of regenerative cooling. Sebastian et al studied on the different types of material used for liquid rocket engines. The studied resulted that among the few other materials, Inconel-718, a nickel alloy can withstand very high temperature upto650°C and is also capable of being manufactured by additive manufacturing. Based on the literature survey it can be seen that, for a combustion chamber the maximum stresses and temperatures occurs at the nozzle throat and the most suitable material for high temperature application is Inconel 718. The gap identified in the literature survey is that all available methods deal with the combustion chamber and no suitable modeling method is identified for estimating the thermal stress behaviour of injector plate of the rocket engine.

2. Experimental Setup

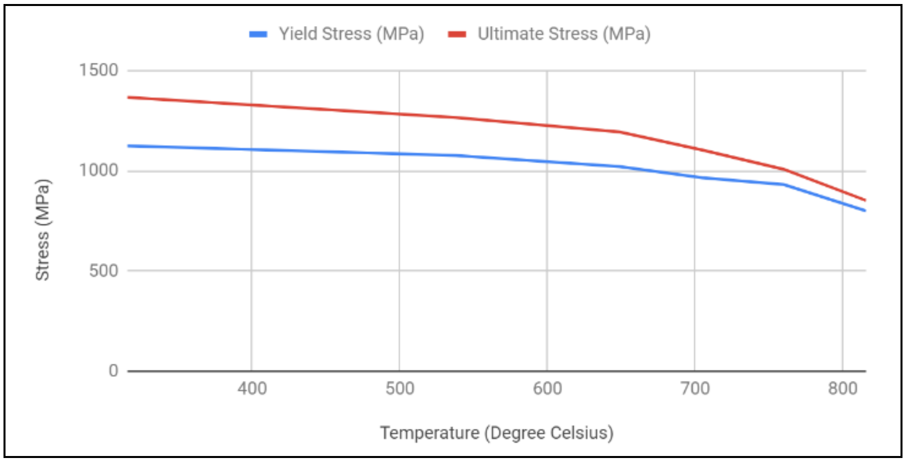
Since, Inconel 718 withstands extreme temperature it is used in high temperature applications. Inconel 718 is also compatible with 3D printing which makes it a better choice of material. Since the injector plate is subjected to very high temperatures, the property of the material also changes with temperature. The following temperature dependant material charts shown in Figure 1 are used for analysis. Further, a nonlinear material model called bilinear isotropic hardening model shown in Fig. is used to capture the effect of plastic region of the stress strain curve.



(a) Young's Modulus and Poisson's Ratio Variation with Temperature



(b) **Coefficient of Thermal Expansion and Conductivity Variation with Temperature**



(c) Yield Stress and Ultimate Stress Variation with Temperature

Figure 1.Variation of Material Properties with Temperature

Figure 1(a) shows that the Young's modulus of the material decreases with increase in temperature and the Poisson's ratio increases with increase in temperature. This is because, at high temperatures the material becomes soft and the stiffness of the material is reduced. Figure 1(b) shows that the coefficient of thermal expansion and thermal conductivity of the material increases almost linearly with increase in temperature. From Figure 1(c) it can be seen that the strength of the material remains stable up to 650°C, after which the strength of the material begins to decrease.

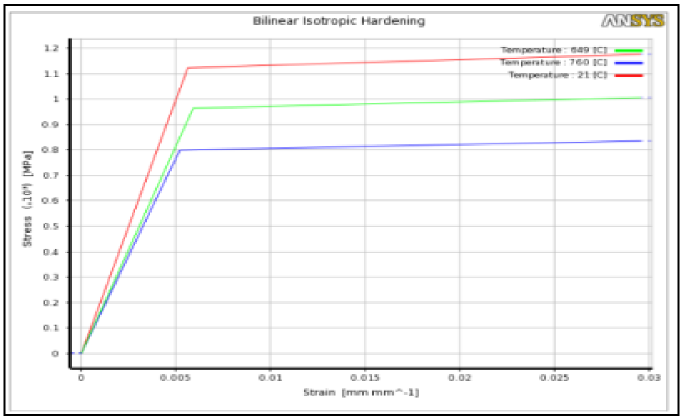


Figure 2. Bilinear Isotropic Hardening Model of Inconel-718

3. Thermostructural Analysis on Existing Injector Plate

Representation of injector plate: The injector plate lies in the top of the combustion chamber connected to it by means of bolts. This injector plate consists of injector elements which sprays the fuel and oxidizer droplets into the combustion chamber. The igniter is mounted on the central port of the injector plate and is responsible for starting the combustion. From Figure 3, it can be seen that the injector plate acts as a cover to the combustion chamber. Hence the injector plate must have sufficient strength to withstand the high temperature and pressure produced by during combustion.

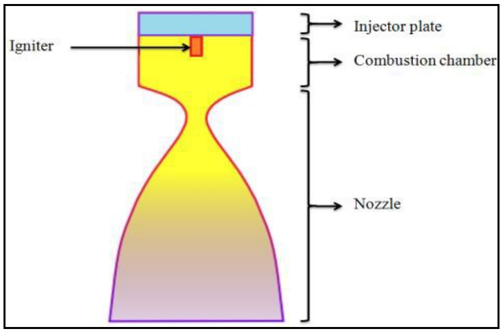


Figure 3. Schematic Diagram of Rocket Engine

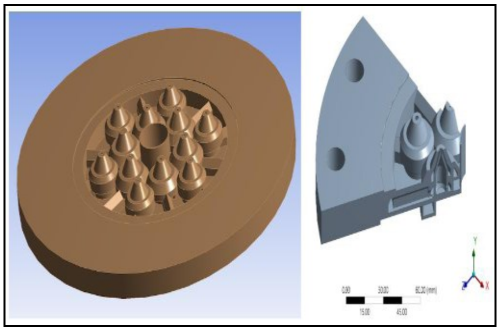


Figure 4. CAD model of Injector Plate

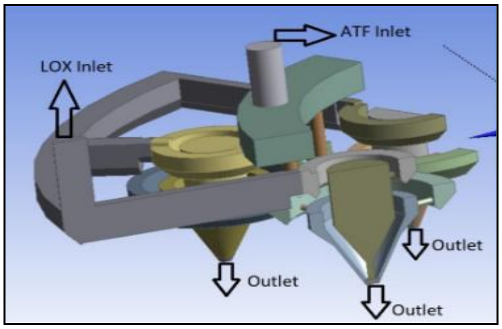


Figure5. Fluid Domain of Injector Plate

CAD model of injector plate: The injector plate consisting of 18 injector elements which are arranged in a concentric circular pattern is taken for analysis. Inside of the injector plate, channels carrying the fuel (ATF) and oxidiser (LOX) are present. Bolt holes are provided to interface the injector plate with the thrust chamber. The centre of the injector plate is given provision for mounting the igniter. Since analysis of the entire geometry is a time consuming and a computational extensive process, a 60o sector is modeled for analysis as shown in Figure 4.

CFD boundary conditions of injector plate: The Fluid is extracted from the geometry of the injector plate for performing CFD. The geometry of the fluid should be such that the flow is continuous without any flow discontinuities. The extracted fluid domain is shown in Fig.5. The top two cylinders represent the LOX and ATF inlet and the bottom of the injector elements is the outlet. The 3D Navier-Stoke Equation is used to compute the flow distribution. k-ω model is taken into account for the turbulence which may be generated during the flow. ATF is entering the injector plate from the regenerative cooling jacket of the combustion chamber with a mass flow rate of 0.01 kg/s generated by the feed pump and with a temperature of 375oC which is gained by flowing through the combustion chamber walls. LOX is entering the injector plate a mass flow rate of 0.02 kg/s which is generated by the pump and a temperature of -188oC. The exit pressure of the fluids in the injector elements is taken as 77 bar which is slightly greater than the combustion pressure. A very fine mesh of the size of 2.5 microns is used to model the heat transfer effect accurately.

Pressure and temperature profiles of injector plate: The temperature and pressure plots of ATF surfaces and LOX surfaces are shown in Figure 6 and Figure 7 respectfully.

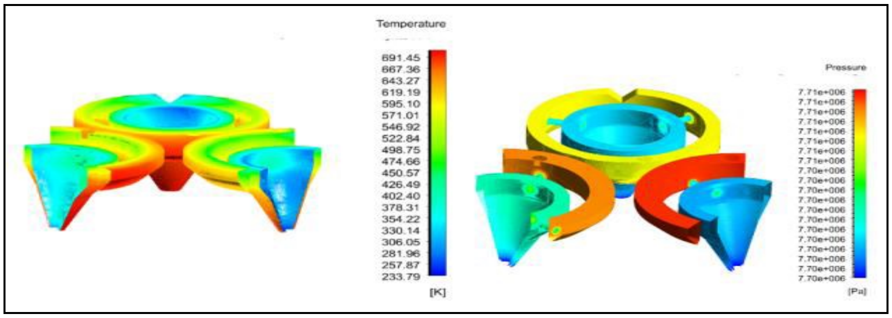


Figure 6. Temperature and Pressure of ATF Surfaces

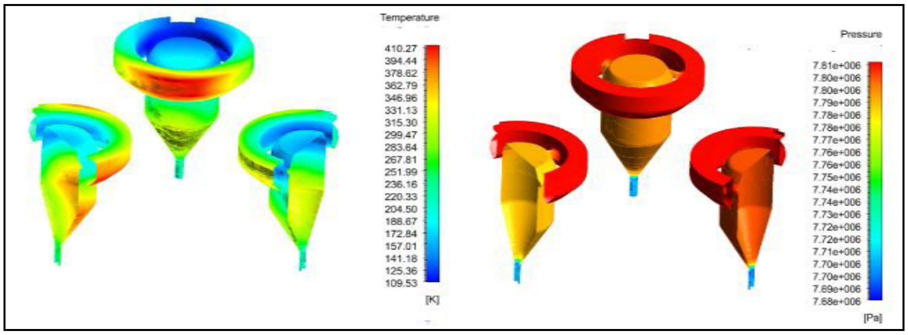


Figure 7. Temperature and Pressure of LOX Surfaces

From Figure 6 and 7, it can be seen that a maximum temperature of 417.8oC and 136.8oC is obtained at the ATF surface and LOX surface respectfully and a maximum pressure of 77 bar and 78 bar is obtained at the ATF surface and LOX surface respectfully. The temperature profile of the entire 60o injector plate is shown in Fig.8. This temperature profile of the solid domain is used for the structural analysis in order to estimate the thermal stresses.

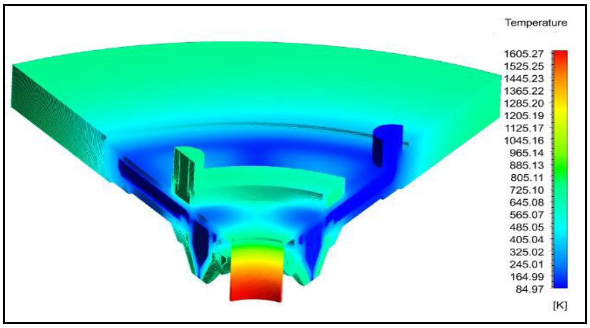


Figure 8. Temperature Plot of Injector Plate

Structural analysis of injector plate: Data which is obtained from the CFD analysis is used as an input for the FEA analysis. Fixed support is given at the bolted support interfaces and a roller support is given at the igniter mounting face. The loads considered include thermal load from temperature of chamber, temperature on LOX and ATF surfaces, structural loads from pressure of chamber and pressure on LOX and ATF surfaces. The boundary conditions for the structural analysis are shown in Figure 9.

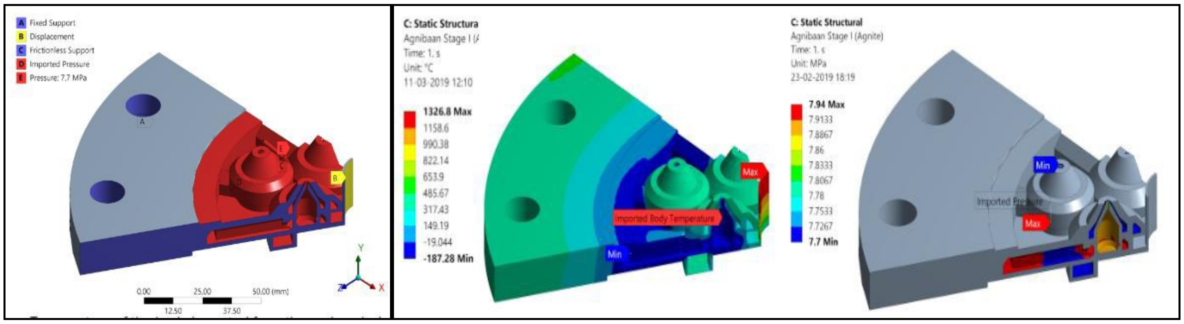


Figure 9. Structural Boundary Conditions of Injector Plate

Figure 10 shows the stress distribution and the deformation plot of the 60o injector plate segment. A maximum yield stress of 1102.6 MPa is observed at the fixed surface. This is due to the Poisson's effect. Except at the V-shaped channel, all other regions have stresses less than 965 MPa, which is the yield stress of Inconel 718 at 650oC. Hence these V shape channels must be avoided for better structural integrity.

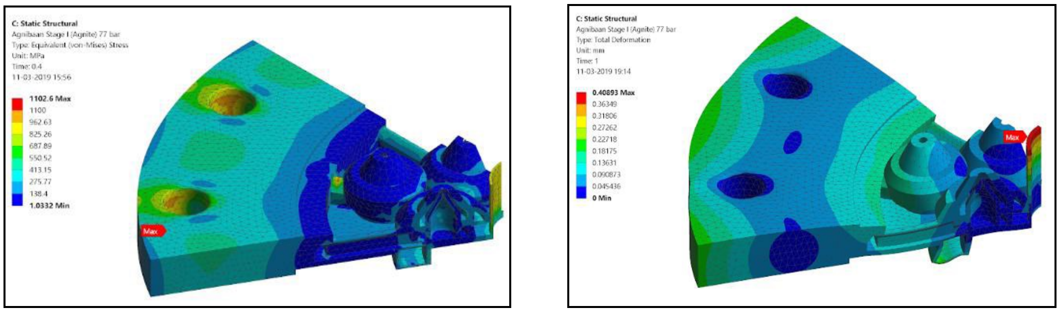


Figure 10. Equivalent Stress and Total Deformation Profile of Injector Plate

4. Thermostructural Analysis on Modified Injector Plate

The injector plate with V shape channels affects the structural integrity of the entire design. But, these v shaped channels are essential to carry the fuel and oxidiser throughout the injector plates and into the injector element and into the combustion chamber. Hence, some material is added to cover up these V shape channels on the surface facing the combustion chamber side. The addition of material also increases the weight of the injector plate to a certain extent. Hence a trade off must be performed to arrive at a design with maximum structural integrity and minimum mass. Material is added to existing injector plate to fill the V shape channels and the same analysis is performed again to obtain preliminary results. The resulting model is shown in

Figure 11, has a thickness of about 20.5mm is being added on the side of the combustion chamber which resulted in increase in mass of about 1.8kilograms. The increase in mass is constrained by the thrust generated by the engine and the maximum payload capacity of the vehicle.

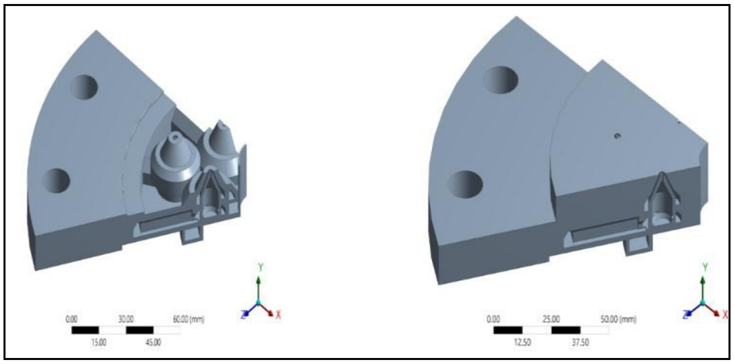


Figure11. Design of Flat Face Injector Plate

The similar method of conjugate heat transfer analysis which is used previously is used in this model also for validation of the thermo structural stresses which the injector plate is subjected to. Since in the flat plate injector plate design it can be seen that a lot of material is being exposed to the hot combustion gases. Hence the surface area of the injector plate which comes in contact with the hot combustion gases increases tremendously. This results in efficient forced convection on the combustion gas side. Because of this a surface temperature of only 610oC is obtained on the hot gas side of the injector plate. Further, the surface temperatures of the fuel and oxidizer walls also vary slightly due to the change in the design. This is due to the fact that the amount of material which carries heat due to conduction is being changed. From CFD analysis it is found that the maximum temperature of about 534.3^{o}C is obtained at the fuel side surface. At the oxidizer surface a maximum temperature of about 91.6^{o}C is produced which is shown in Figure 12. The pressure acting on the surface of the channel walls remains same since the channel geometry remains unchanged for both the design with and without flat face. The results obtained from the CFD analysis is used as an input of structural analysis. The boundary conditions applied are similar to the previous design, except that the chamber pressure acts on the entire surface of the flat face of the injector plate. Hence it can be predicted that the stress concentration effects will almost be negligible and that the stresses obtained will be low than that of the previous design. From the Figure 13, it can be seen that a high stress of 1167 MPa is observed. But this stress is not at the face of the injector plate which is facing the combustion chamber. But the high stress instead occurs at a location where the bending stress is high due to a stepped profile of the flange connecting the injector plate. Those regions of high stresses can be minimized by providing a fillet at those interfaces. Further, a deformation of 0.65 mm is obtained at the surface of the injector plate facing the combustion chamber. This deformation direction is towards the combustion chamber side.

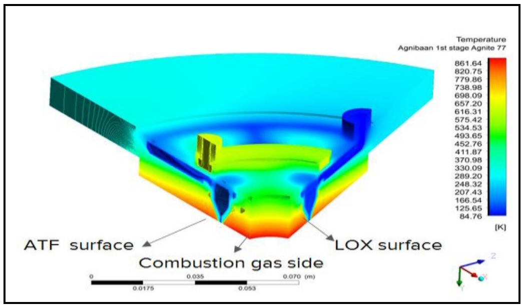


Fig.12. Temperature Profile of Modified Injector Plate

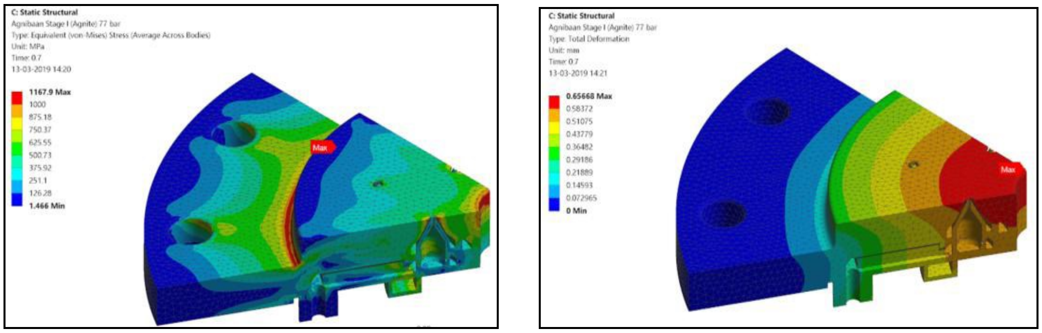


Fig.13. Equivalent Stress (top); Total Deformation (bottom)

This result can be interpreted that the pressure effect of pushing the injector plate away from the combustion chamber is dominated by the temperature effect which is trying to pull the injector plate towards the injector plate. The effect of modifying the injector plate geometry is shown in Table 1.

Table 1 Comparison of Two Designs

	Exisiting injector plate	Modified injector plate
Mass (kg)	5.2	7
Maximum temperature (°C)	1158	587
Maximum equivalent stress (MPa)	1102.6	1167.9
Maximum total deformation (mm)	0.4	0.65

5. Optimization Of Injector Plate

In this section, the stresses in injector plate is tried to reduce and at the same time, keeping the mass of injector plate minimum. A sensitivity analysis was done by taking all the parameters which can affect the mass of the injector plate. Figure 14 shows that E, which denotes the flange thickness is the only parameter which has a significant effect on the mass of the injector plate

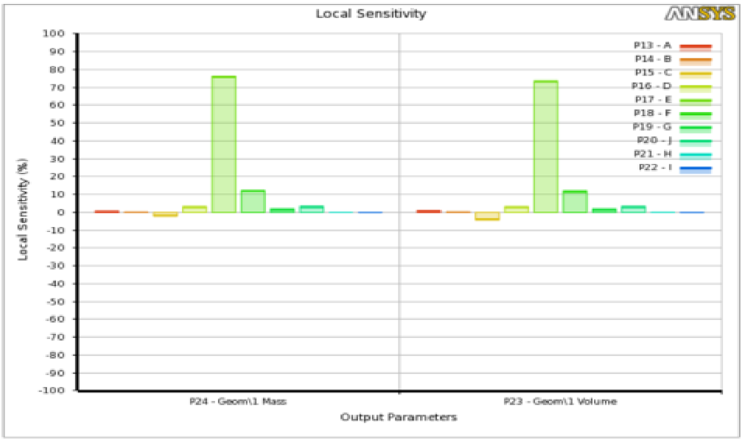


Figure 14. Sensitivity Analysis of Modified Injector Plate

A Design of Experiments (DOE) study is done in order to arrive at a set of design points to study the design of the injector plate. The input parameter which vary is taken as flange thickness and the output parameters which change due to the change in input parameter of the input parameter includes, mass (kg) and equivalent stress (MPa). Table 2 shows the DOE points which is obtained by following Central Composite Design.

Table 2 Design of Experiments Table

Flange thickness (mm)	Mass (kg)	Maximum Stress (MPa)
5	4.458	731.73
7.5	5.112	739.56
10	5.772	763.06
12.5	6.426	803.48
15	7.086	925.83

Based on the design of experiments a response surface which relates the behavior of the output parameter with respect to the change in input parameter is obtained. Figure 15. shows the response of mass to the change in the flange thickness. Since increasing the thickness directly increases the amount of material used, a linear increase of mass with respect to increase in flange thickness is observed. The response surface of maximum equivalent stress also shows that the increase in flange thickness increases the maximum equivalent stress produced. This is because, when more material is available, these material increases the resistance offered to the deformation, hence stress increases.

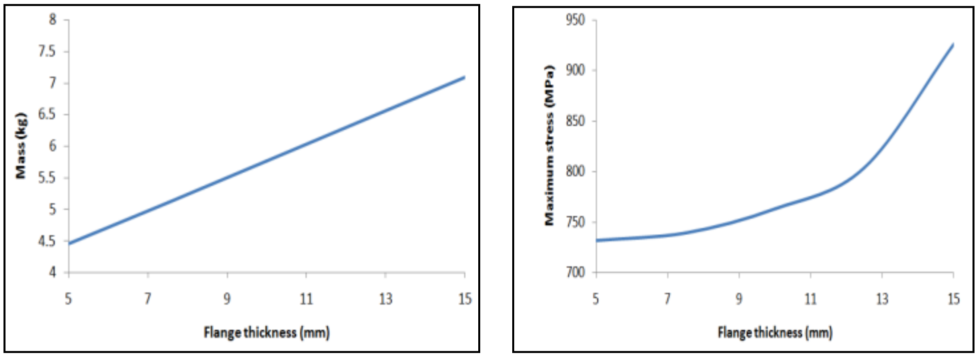


Figure15. Response Surface of Mass and Maximum Stress with Flange Thickness

The response surface which is obtained is used to generate a equation from which maxima and minima can be calculated and the optimization is performed genetic algorithm. The response surface is used to optimize the design for maximum equivalent stress which is less than 850 MPa, i.e., less than the yield stress at 650 oC with a factor of safety of 1.25. The objective of the problem is to minimize the mass. From the optimized data points obtained in table 3, the flange thickness of 5 mm is selected since it has a minimum mass and the stress also appears to be less than the criteria provided. The results obtained are purely by statistical methods. Hence the selected point must be verified again using numerical results for trustworthiness. Fig.15. shows the Equivalent stress distribution and total deformation of the injector plate design of 5mm flange thickness. The maximum stress which is obtained by numerical analysis is 763.06 MPa which is in validation with the statistical method.

Table 3. Optimized Data Points

Flange thickness (mm)	Mass (kg)	Maximum Stress (MPa)
5	4.458	763.06
6	4.72	752.54
7	4.98	742.38

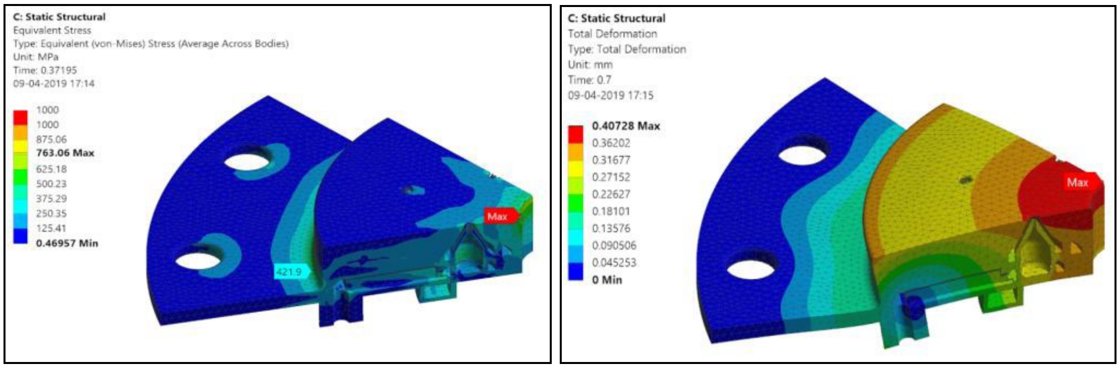


Figure16. Equivalent Stress and Total Deformation of Optimized Injector Plate

6. Conclusion

In this work 3D CAD models injector plate which includes a number of injector elements are created. The injector plate is analysed using Conjugate Heat Transfer method. The results showed that the stress concentration was seen due to the presence of sharp edges and corners. Modification of the injector plate has been numerically simulated to improve the strength and reduce the mass of the injector plate. To reduce the mass, different design trails have been analyzed on the modified injector plate design. The optimization was performed using statistical method, RSM. The results obtained from these statistical methods were checked again using numerical method which shows the results obtained to be accurate. Thus, the mass of the flat face injector plate was reduced to 4.45 kg from 7.08 kg. This showed in the mass reduction of 37.14%. In aerospace components, this kind of mass reduction is very much essential as it plays a major role in improving the performance of the vehicle. Further this reduction in mass does not affect the structural integrity of the injector plate.

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