Coupled Thermal – Structural Finite Element Analysis for Exhaust Manifold of an Off-road Vehicle Diesel Engine

Sweta Jain, AlkaBani Agrawal

Abstract—This paper present the Sequential Coupled Thermal - Structural Analysis to investigate the associated thermal stresses and deformations under simulated operational conditions close to the real situation on different materials. Analysis carried out by reference environmental testing conditions; in different ambient temperatures on different materials i.e. cast iron, structural steel.The finite element analysis software ANSYS Workbench 14.0 used to calculate the linear steady state temperature distribution under the thermal field & structural analysis. Thermal analysis calculates the temperature distributions and related thermal quantities in an exhaust manifold. Structural analysis takes inputs from thermal analysis to calculate deformation, stress and strain. FEM analysis is done by using tetrahedral element of first order and convergence test is performed for structural load. The purpose of this analysis is to ensure the appropriateness of material for the defined design from the view point of serviceability of the exhaust manifold. Selected details and results of the overall investigation are presented and discussed within the framework of this paper.

Index Terms — Exhaust Manifold, FEM, Heat Transfer Coefficient, Thermal-Structural Analysis.

I. INTRODUCTION

Exhaust manifold is a part of diesel engines which are required to collect the exhaust gases from the cylinder head and send it to the exhaust system. The exhaust manifold plays an important role in the performance of an engine system. Particularly, the efficiencies of emission and the fuel consumption are nearly related to the exhaust manifold. The manifold may be a casting or fabricated of relatively light material. The purpose of the exhaust manifold is to collect and carry these exhaust gases away from the cylinders with a minimum of back pressure. Exhaust Manifolds are affected by thermal stresses and deformations due the temperature distribution, heat accumulation or dissipation and other related thermal quantities. In a today scenario, there is high competition between Off-road vehicle manufacturers. The Objective of our analysis is to find out the suitable material by comparing thermal stresses and deformations induce by temperature mapping on different materials for exhaust manifold of off-road vehicle diesel engine.

In this paper we investigate an exhaust manifold of an off-road vehicle diesel engine. In First Step, FEM analyses are done on a component by using tetrahedron element of first order and convergence test is performed for structural load, to know the optimum element size. Thermal analysis performed to determine temperature mapping, heat flow and overall heat transfer characteristics in a second step.

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The results are sequentially used as an input in a stress, strain and deformation calculation and to confirm whether geometry of the component meets a particular conductivity requirement. Input values of temperature are collected via experimental testing's observation for analysis. Experimental values of temperature distribution are validated with the result of FEA steady state thermal analysis.

II. REVIEW OF PREVIOUS WORK

According to Zhu Maoqina [1] Calculation on the exhaust manifold is carried out based on coupling of CFD and FEA software the distribution of temperature and thermal stress of exhaust manifold of stainless steel is demonstrated.

YasarDeger [2] Observed that the efficiency of the interdisciplinary multi physics analyses and the quality of their results are however highly dependent on the possibility to access the knowledge and expertise of company specialists in finite element applications, materials sciences and fluid dynamic. A typical example of such a close cooperation at SulzerInnotec was the numerical investigation of the thermo mechanical stresses in the exhaust manifold of a diesel engine with active water cooling system. CFD analyses for three stationary operational conditions with variable cooling flow were performed for this exhaust manifold aiming to determine specific temperature and pressure distributions. The fluid flow and the heat transfer through the exhaust manifold were computed correspondingly by CFD analyses including the conjugate heat transfer.

HavvaKazdalZeytin [3] shows that ductile cast irons are used as high temperature materials in internal combustion engines, because they are micro structurally stable at high operating temperatures. SiMo granular graphite cast irons contain Fe2 MoC and M6C carbide precipitates due to their higher concentration of both silicon and molybdenum. The microstructure of these cast irons consists of carbides dispersed within the ferrite matrix. The micro structural change and the crack formation mechanism in manifolds produced from SiMo ductile iron are studied.

J.DavidRathnaraj [4] shows that automotive engine operates under severe thermo mechanical loading condition, the operating temperature increases up to 800°C from ambient temperature and large thermal stress is induced by temperature gradient and geometrical constraints. This thermo mechanical coupling is one of critical problems in automotive engineering. For instance, most of the crack found in the stainless steel exhaust manifold is caused by out-of-phase thermal fatigue occurring at high temperature.

Bin Zou, [5] reports that, the exhaust manifold is close to the engine part in automotive exhaust system, because the cylinder discharge gas temperature can reach 800°C above, the tail gas heating effect is obvious. Because the thermal stress that tail gas heating caused can be as high as hundreds of Mpa, it can also lead to thermal fatigue and cause structural fracture. Temperature has great influence on material mechanical properties, so it is necessary to take the influence of the temperature pre-stress on exhaust manifold vibration characteristics into account.

III. ANALYSIS METHODOLOGY

The flow and temperature field is solved using thermal solver. Surface temperature and inner temperature are measure by experimental testing method. Then, applies the boundary condition that consist of a constant temperature and constant heat transfer coefficient on the inner surface of the exhaust manifold and constant heat transfer coefficient and variable ambient temperatures on outer surface of the exhaust manifold. The temperature distribution is calculated and thermal stress analysis is done on ANSYS Workbench 14.0. For investigation, consider assumption for steady state heat transfer and Linear static structural analysis. For a steady-state (static) thermal analysis in Mechanical, the temperatures {T} are solved for in the matrix:

$$[K(T)]\{T\} = \{Q(T)\}$$

Assumptions:

- No transient effects are considered in a steady-state analysis
- [K] can be constant or a function of temperature
- {Q} can be constant or a function of temperature
- Fixed temperatures represent constraints {T} on the system.

For a Linear static structural analysis, the displacements {x} are solved for in the matrix equation below:

$$[K]\{x\} = \{F\}$$

Assumptions:

- [K] is constant
  – Linear elastic material behavior is assumed
  – Small deflection theory is used
- {F} is statically applied
  – No time-varying forces are considered
  – No damping effects.

IV. FINITE ELEMENT ANALYSIS

To simulate the thermally induced stress, strain, deformations induced by the temperature distributions. FE simulations have been performed using ANSYS 14.0.The model consisted of 3.0 mm tetrahedral element of first order.

A. MATERIAL PROPERTIES RELEVANT FOR THE FE ANALYSIS

The material properties of Cast iron (FG 260) and Structural steel are sensitively dependent on the temperature. Consider the average temperature under operational conditions and as a conservative approach, following material properties used for simulation purposes.

Material Properties	Unit of Measure ment	Grey Cast Iron (FG 260)	Structural Steel
Density	kg m^-3	7200	7850
Isotropic Thermal Conductivity	W m^-1 C^-1	52	61
Coefficient of Thermal Expansion	C^-1	1.1E-05	1.2E-05
Young's Modulus	Pa	1.10E+11	2.00E+11
Poisson's Ratio	--	0.26	0.30

B. BOUNDRY CONDIIONS

The investigated exhaust manifold is mounted on engine wall by two mounting flanges and practically fixed, that means there is no displacement are possible in normal direction to the surfaces which are connected to adjacent devices. The hot flue gases which flow inside the exhaust manifold have a maximum temperature of 670ºC with the ASSUMED inside heat transfer coefficient of 70 W/m²°C and consider the ambient temperature 25°C, 35°C and 50°C covering natural to highest ambient temperature and assumed outer heat transfer coefficient of 30W/m²°C. The surface temperature on mounting flanges is 150°C.Figure 1 shows the FE-Model with corresponding thermal boundary conditions.

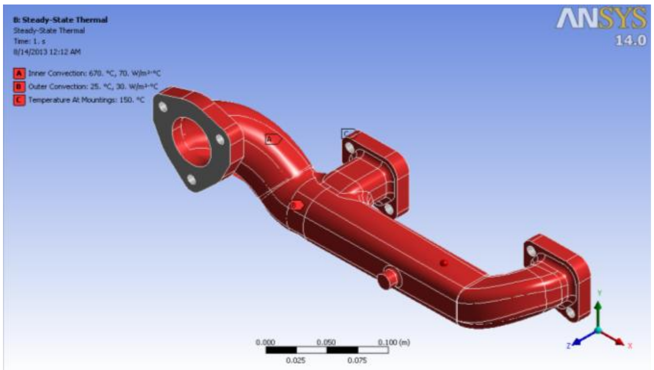


Figure 1 – Boundary Condition Thermal

C. THERMAL MAPPING ANALYSIS AND RESULTS

The thermal mapping is done by solving steady state thermal analysis of the component by using ANSYS Workbench 14.0. Outer surface of component is exposed to environment (i.e. air flowing in the chamber or the still air around the engine,) on which constant heat transfer coefficient applied with variable ambient temperatures 25°C, 35°C and 50°C. Outer and inner heat transfer coefficient are assumed respectively 30W/m²°C and 70 W/ m²°C, to calculate thermal loads on the exhaust manifold. Thermal analysis is done for thermal mapping on the complete body that will calculate all the nodal thermal values dependent on the thermal resistance of the materials. This temperature mapping is transfer to the structural analysis for calculation of expansion of the structure this will gives the thermal stress and thermal strain results.

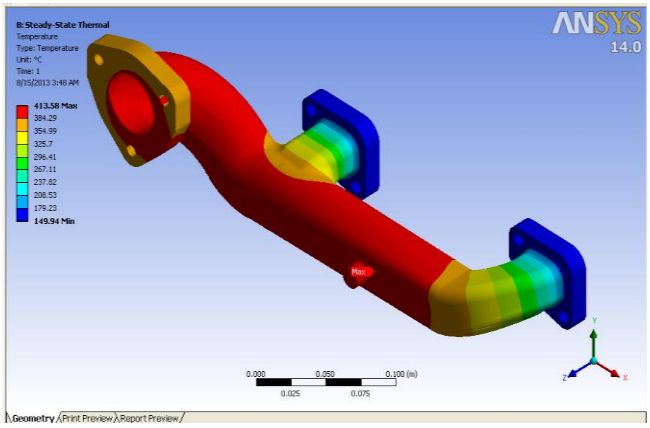
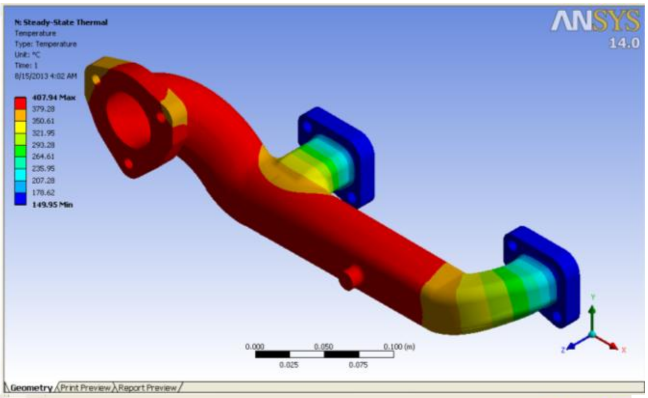


Figure 2- Temperature Mapping of CI, Ambient Temp. 25°C



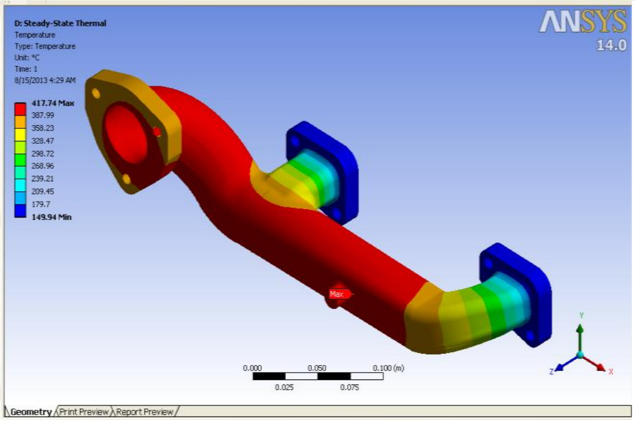


Figure 3 - Temperature Mapping of SS, Ambient Temp.25°
Figure 4 - Temperature Mapping of CI, Ambient Temp.35°C

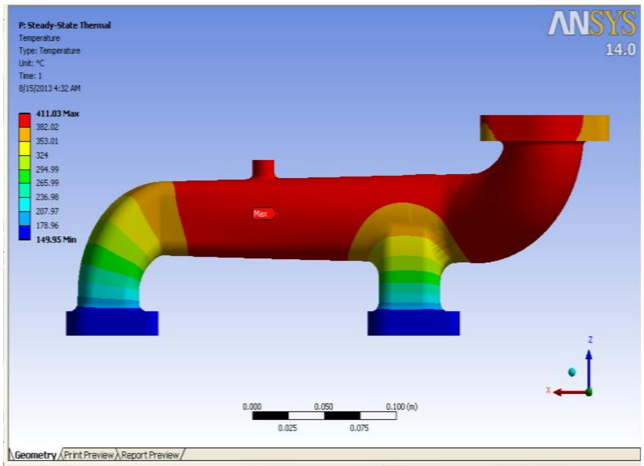


Figure 5 - Temperature Mapping of SS, Ambient Temp.35°C

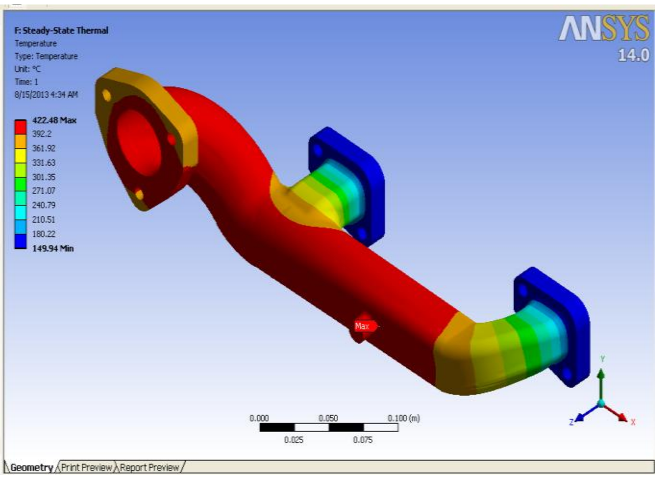


Figure 6 - Temperature Mapping of CI, Ambient Temp. 50°C

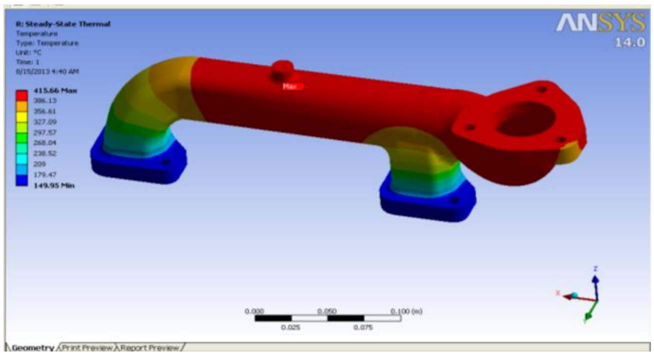


Figure 7 - Temperature Mapping of SS, Ambient Temp.50°C

In thermal analysis, Figures (2 to 7) shows that the temperature mapping on different materials namely Cast Iron (FG 260) and Structural Steel, as a result of applied experimental inner surface temperature. Temperature mapping shows that Variation of temperature in the component is depending on the thermal propertiesof materials used for exhaust manifold analysis. As the boundary conditions are same for both the materials, the maximum temperature region is similar only the variation in temperature gradient exists. The above figures also shows that the maximum temperatures around the exhaust manifold pipe area and minimum temperatures are at the mounting flanges attached to the engine wall due to the steady state and comparative high thickness of mounting flanges of exhaust manifold. This means that the evolution of the temperature at every points of the structure must be computed from gas flows inside and outside the manifold. Based on the thermal loading, the analysis aims to compute the stress and strain response of the structure. This temperature load is then transfer to the structure solver by coupling of thermal and structural solver.

D. SEQUENTIAL STRUCTURAL ANALYSIS RESULTS

Temperature Mapping Results are transfer to the ANSYS static structural solver for calculation of expansion of the structure this will gives the thermal stress, strain and deformation results. Two different materials with three different ambient temperature cases are evaluated in terms of von misses stress and equivalent elastic strain. Figures (8, 9, 12, 13, 16 & 17) shows a typical deformation plot and Figures (10, 11, 14, 15, 18 & 19) Shows corresponding stress distributions. As one can easily see, the maximum stresses are of the same order of the magnitude as the yield stress. In the cases of Cast Iron (FG 260) and Structural Steel the stress concentration and deformation areas remain the same and both are increasing with increasing ambient temperature due to the geometrical shape and boundary condition of the Exhaust Manifold. [Unit - The deformation are given in meter and Stresses are in MPa.]

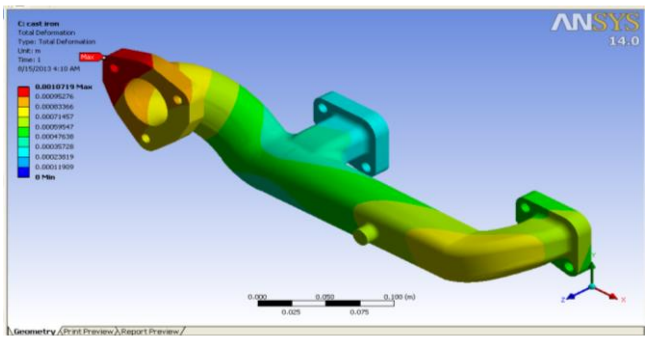


Figure 8 – Total Deformation of CI, Ambient Temp.25°C

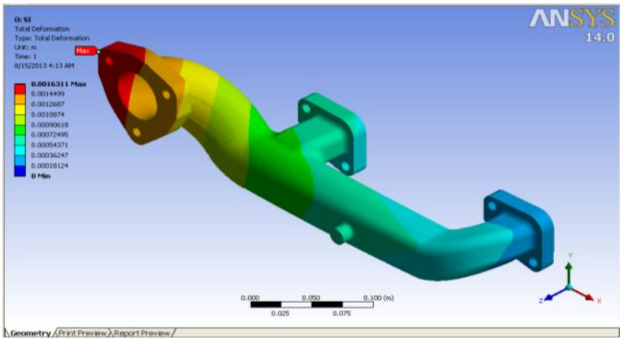


Figure 9 – Total Deformation of SS, Ambient Temp.25°C

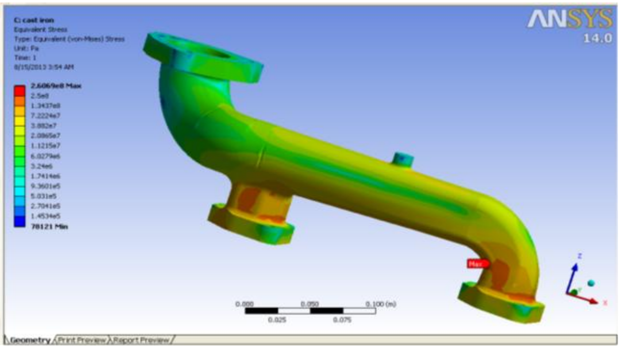


Figure10 – Thermal Stress of CI, Ambient Temp.25°C

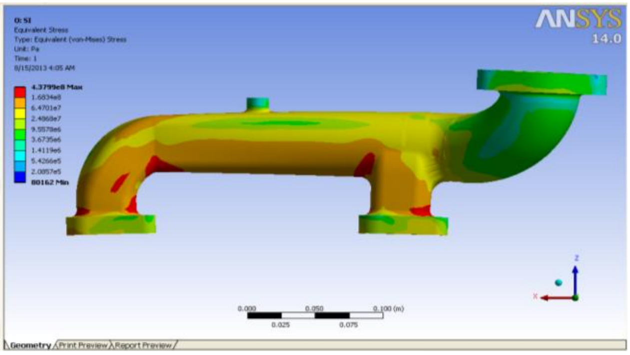


Figure 11 – Thermal Stress of SS, Ambient Temp.25°C

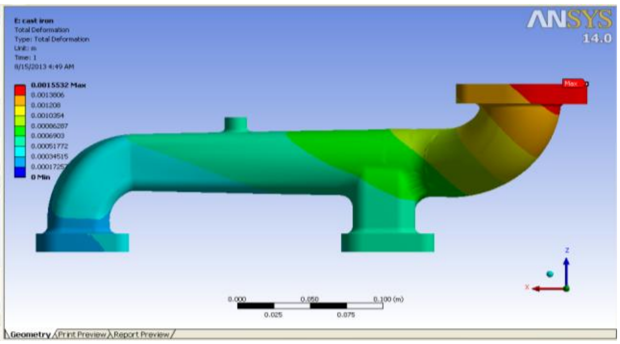


Figure 12 – Total Deformation CI, Ambient Temp. 35°C

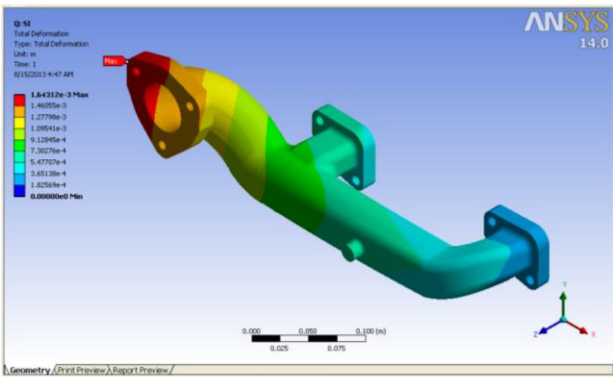


Figure 13 – Total Deformation of SS, Ambient Temp.35°C

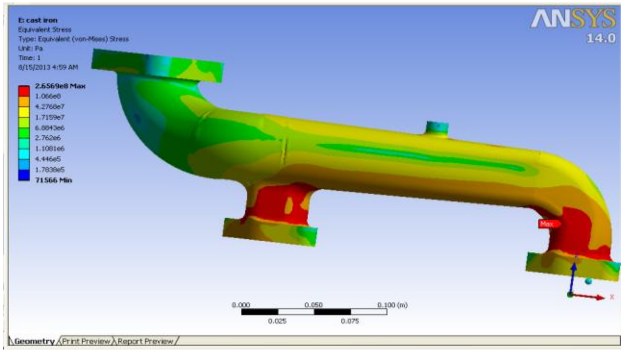


Figure 14 – Thermal Stress of CI, Ambient Temp.35°C

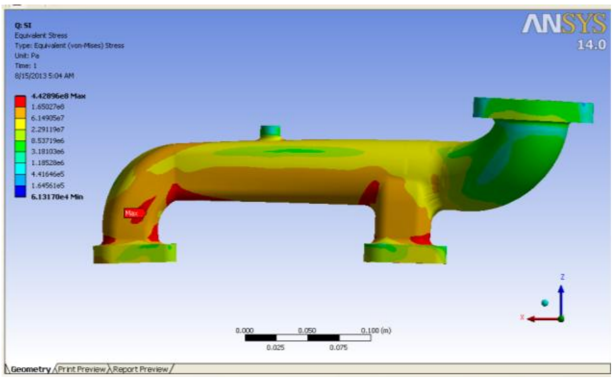


Figure15 – Thermal Stress of SS, Ambient Temp.35°C

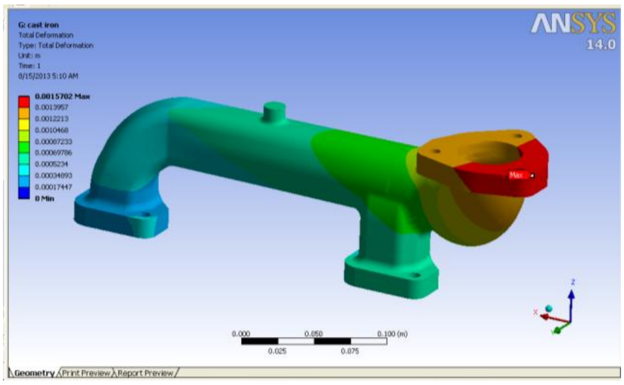


Figure 16 – Total Deformation CI, Ambient Temp. 50°C

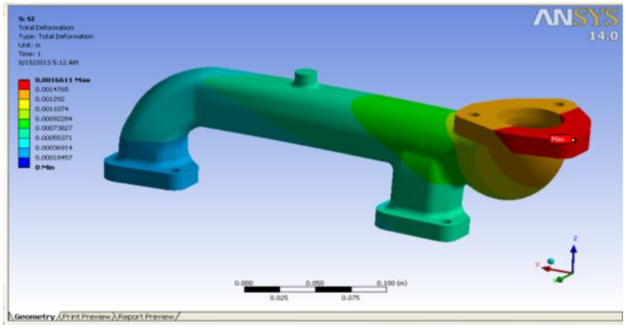


Figure 17– Total Deformation of SS, Ambient Temp 50°C

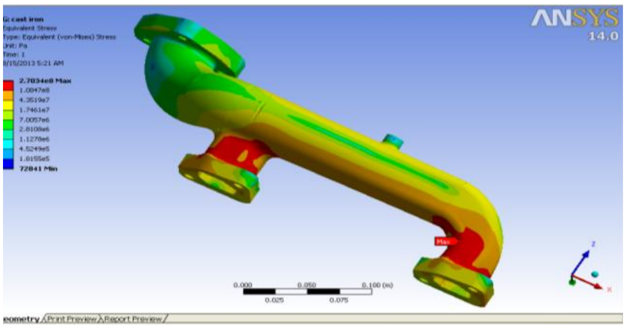


Figure18 – Thermal Stress of CI, Ambient Temp.50°C

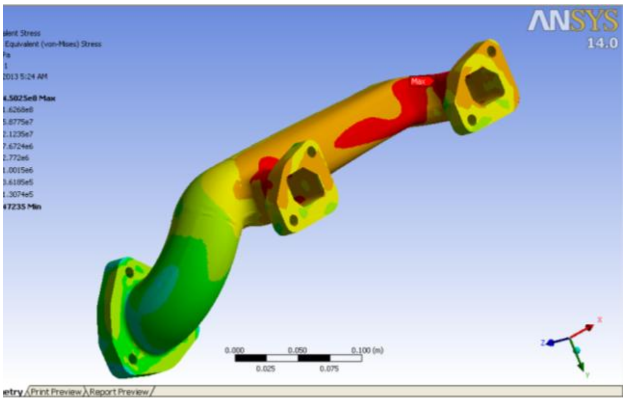


Figure 19– Thermal Stress of SS, Ambient Temp. 50°C

The one advantage of the sequential coupled thermal – structural FE simulations as investigated in the presented case is that the geometry can be easily adapted to possible modifications and used for any "Goal Seek…"analysis tool.

V. RESULTS

The three ambient temperatures respectively 25°C, 35°C and 50°C is taken with assumed convective coefficient of 30W/m²°C.

1. The result of FE simulations of temperature distribution on Grey Cast Iron with ambient temperature 35°C, validated with experimental data.
2. The result of FE Simulations of static structural are mentioned in a tabulated form -

Table 1 – Cast Iron [FG260]

Ambient Temperature (°C)	Stress (MPa)	Deformation (m)
25	260	0.0010719
35	265	0.0015532
50	270	0.0015702

Table 2 – Structural Steel

Ambient Temperature (°C)	Stress (MPa)	Deformation (m)
25	437	0.0016311
35	442	0.0016431
50	450	0.0016611

VI. CONCLUSION

From the investigated result of Sequential Coupled Thermal - Structural FE analysis, observed that the critical area of thermal stress concentration and deformation on both the materials are similar. Stress concentrations can be interpreted as significant indices for extreme temperature levels and temperature gradients. The Results shows that both studied material, Cast Iron (FG 260) and Structural Steel are appropriate for the investigated Exhaust Manifold of off-road vehicle diesel engine.

The investigated FE model of Exhaust Manifold of off-road vehicle diesel engine will be reuse for further investigations.

Some suggestions are listed below, which may be guide to significant improvements in reduction of thermal stresses

1. Modification of the Geometry.
2. Other Material and Grades can be choosing as an option with adequate mechanical properties at high temperatures.

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REFERENCES

[1] Zhu Maoqina, LvJuncheng and ZhongXiangbo "Development for Stainless Steel Exhaust Manifold and CAE Analysis". Advance Material Research Vol. 462. (2012).Trans Tech Publications, Switzerland.

[2] YasarDeger*, BurkhardSimperl*, Luis P. Jimenez* "CFD-FE-Analysis for the Exhaust Manifold of a Diesel Engine", *SulzerInnotec, Sulzer Markets and Technology Ltd, Winterthur, Switzerland and * *Guascor I+D S.A., Miñano, Spain.(2004).

[3] HavvaKazdalZeytin "Effect of Microstructure on Exhaust Manifold Cracks Produced From SiMo Ductile Iron" Journal of Iron and Steel Research, International, 16, 3, May 2009.

[4] J.DavidRathnaraj "Thermomechanical Fatigue Analysis of Stainless steel Exhaust Manifolds", IRACST – Engineering Science and Technology: An International Journal (ESTIJ), ISSN: 2250-3498, Vol.2, No. 2, April 2012.

[5] Bin Zou, Yaqian Hu, Zhien Liu,Fuwu Yan and Chao Wang in Zou," The Impact of Temperature Effect on Exhaust Manifold Thermal Modal Analysis" Research Journal of Applied Sciences, Engineering and Technology 6(15): 2824-2829, 2013 ISSN: 2040-7459; e-ISSN: 2040-7467.

[6] ANSYS Tutorials "Introduction to ANSYS Mechanical Guide".

[7] "Heat Transfer Coefficient Values" http://www.thermopedia.com.

[8] "Central Farm Machinery Training and Testing Institute", Tractor Nagar, Budni (M.P.).

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