Investigation and Recommendation of Exhaust Manifold Damage through Conjugate Heat Transfer Analysis

K. Rajesh[1] S. Ramkumar[2] N. Sadasivan[3] N. Aravindhan[4] A. Balajikrishnabharathi[5]
[1,3,4,5]Assistant Professor
[1,3,4,5]RMKCET- Chennai, India [2]Ford India Private Limited- Chennai, India

Abstract— The rapid advances in computer and simulation technology make it possible to model complex geometrical shapes, material behaviour and thermal stresses, and to analyze the associated deformations and stresses under simulated operational conditions close to the real situation. The efficiency of the interdisciplinary metaphysics-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 volume applications, materials sciences and fluid dynamics. A typical example of the numerical investigation of the thermo mechanical stresses in the exhaust manifold of an IC engine. In a first phase, CFD analyses for flange and manifold pipe assembly with test conditions with guesses operating boundaries were performed for this exhaust manifold aiming to determine sensible 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. The temperature distributions of the solid part of the CFD mesh were neglected. Second phase of the modelling compares the existing model with the proposed model for test bed conditions for the same design model with similar approach. They were analyzed subsequently using the CFX V12 model of this component, consisting of 190000 elements, to quantify related temperature distribution and thermally induced stresses, in a two-way-coupling approach and considering nonlinear material behavior. The interpolation of the temperature data was done automatically in CFX solver. Selected details and results of the overall investigation are presented and discussed within the framework of this paper.

Key words: CFD Coupling, Heat Transfer, Thermal Stress

I. Introduction

The analysis of exhaust manifold is very complex as it is exposed to very high temperatures and the simulation should be done taking into consideration the effect of temperature on modulus of elasticity, elastic-plastic material curves and fatigue properties. As exhaust manifold is exposed to high temperature the oxidation and creep considerations become critical [1]. Exhaust manifold designs are validated in thermal shock test of the Engine. Exhaust manifolds are parts of diesel engines sensitive to crack damage. Even improved materials like cast alloys suffer from relatively high operational temperatures which can lead to significant stresses and displacements. Moreover, welding process is expensive due to high technology welding robots and time consumption. The pipe and flange are exposed to large thermal stresses that are applied when welding [2-3].

Welding defects can occur when welding; some of the defects can take shape of small pieces of material. Present investigation is to prove that the proposed non welding joint technique is more advantageous than the conventional method through CFD techniques [4-6].

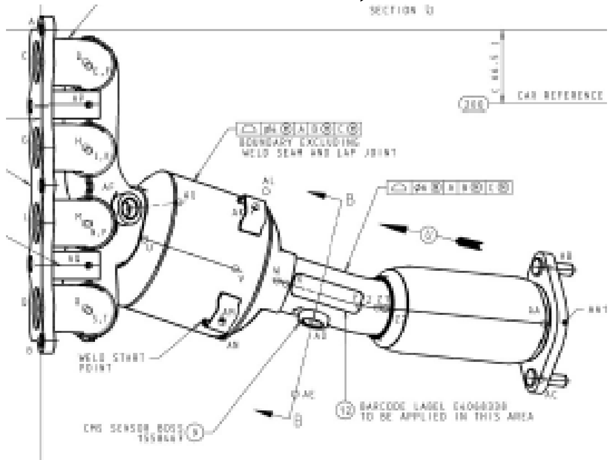

Fig. 1: Exhaust Manifold

A. *Proposed Design Modification:*

Having said that major cause of the failure was identified as an uneven thermal stress created on the three different material junctions near the manifold pipe and flange of the exhaust assembly [7-8]. Present study proposes a new assembly methodology of pressurized pipe fitting that avoids welding in the junction. The proof has been done through conjugate heat transfer analysis [9].

B. *Model 1(Conventional design with CI & MS Tubes):*

Since cast iron flange base, mild steel exhaust pipes and alloy welding have different coefficient of volumetric thermal expansion, thermal conductivity and surface finishing, no unique thermal behaviour is expected.

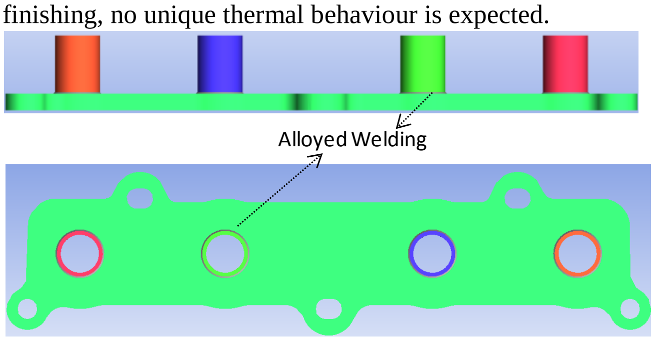

Fig. 2: Conventional Exhaust Manifold Assembly with Welding In the Root

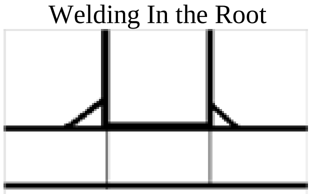

Fig. 3: Isometric View of Assembly And Schematic Representation Of Three Material Junctions

C. *Proposed Design:*

Many research studies prove that any non-welding techniques could be more advantageous to overcome the present failure scenario. Manifold pipes were manufactured with the diameter of interference fit with the flange and pressurized to fit with the flange hole through hydraulic systems.

Present recommendation was much advantageous than the conventional methods in thermal distributions. It can be showcased through uniform thermal distribution on the flange and the pipe base for the continuous running of the engines. Since it differs with the few local temperature gradients with the conventional models, it is very difficult to identify through experimental setups. Present advanced computational fluid dynamic techniques can be much suitable to visualize the uniform temperature distributions and local temperature gradients.

For domain descritization, ICEM CFD is the meshing software used for meshing the whole domain. Though we had an option of unstructured tetra and structured hexa meshing, we adopted hexa to increase the accuracy as reported in most of the literatures. It has the following forms; blocking, fluid domain separation, boundary naming and meshing.

Mesh file with approximately 1.8 lakh hexahedral meshes was written and exported to CFX pre-processing tool. The meshing statistics for the structured Hexa meshing is given in the below drawing. This shows the total number of meshes that the component has been divided into which amounts to 182812 elements to be precise.

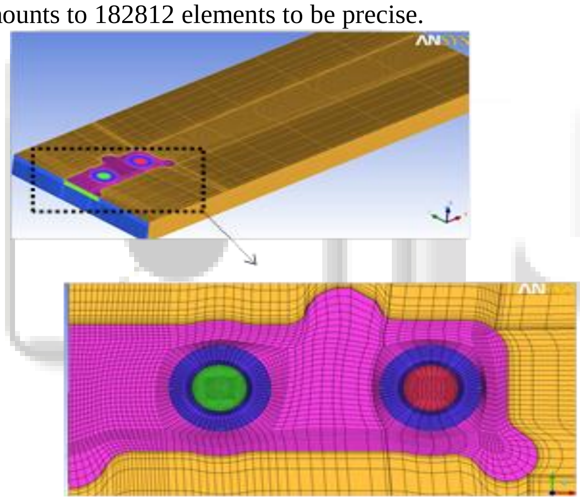

Fig. 4: Structured Hexa Meshing From the Bottom View

II. CONJUGATE HEAT TRANSFER

Conjugate heat transfer analysis is the advanced method to couple computation heat fluid dynamics and thermal distribution. It solves fluid parameters first and establishes thermal equilibrium simultaneously.

A. *Computational Fluid Dynamics:*

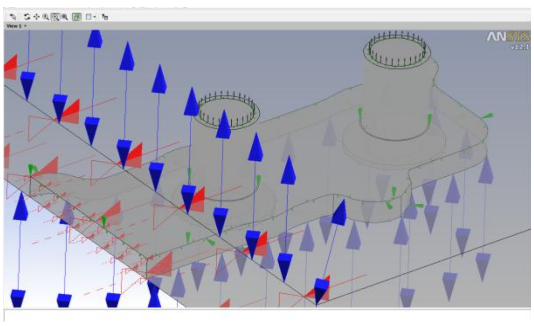

Fig. 5: Computational Fluid Dynamics

Current domain consists of half of the model and the boundary on the separation portion was named as a symmetry boundary. Inner fluid inside the mild steel pipe is named as hot fluid whose inlet is 90 KPa and 800 K as a total pressure and temperature. Outlet boundary is fixed as 0.1 Kg/s as a mass flow rate of the pipe.

External ambient domain is represented as a ambient air with atmospheric temperature and pressure. Remaining two solid domains; mild steel pipe and cast iron were initialled with ambient temperatures. All the domain interfaces were coupled as fluid to fluid, solid to fluid and solid to solid two ways coupling appropriately.

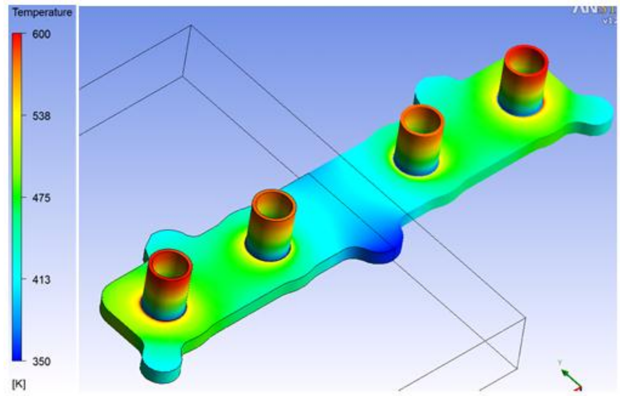

Fig. 6: Temperature Distributions on Manifold Assembly

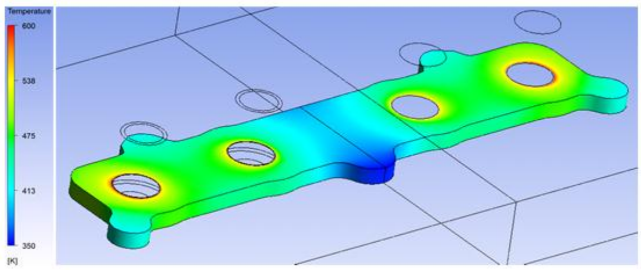

Fig. 7: Temperature Distributions

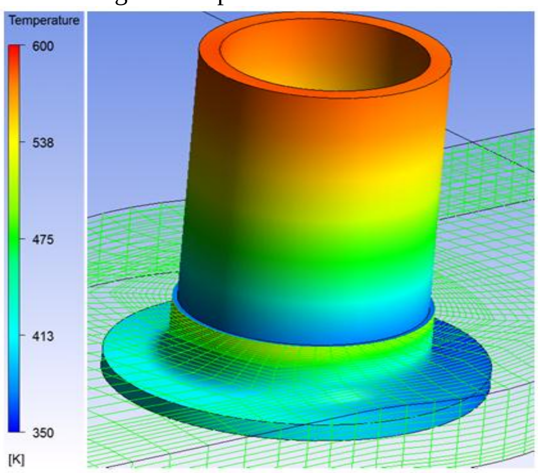

Fig. 8

III. HEAT TRANSFER ANALYSIS

A. *High Temperature Properties:*

Oxidation resistance of the stainless substrate is enhanced by diffusion of the aluminium coating.AL409 is resistant to 1550°F (843°C). AL439 is resistant to 1700°F (927°C).At temperatures above 800°F (427°C), the diffused aluminum coating provides long-term resistance to hot salt attack and wet salt pitting in front pipes, converter shells and intermediate pipes. The diffused aluminium coating will take on a dark grey appearance and is subject to cosmetic red rusting. Creep and fatigue strength equal to the stainless steel substrate.

B. Pipe Material: Aluminized Steel Tube:

Since it is a test case, the material specifications were changed as mentioned below to check with the temperature distribution.

- Flange Material : SS316
- Pipe material : Aluminised Steel Tubes
- Exhaust Pipe-Aluminized Steel

Excellent Resistance to Pitting Corrosion from Road Salt and Muffler Condensate corrosion.

C. Coating:

The coating is Type 1 Aluminized containing approximately 91% aluminum and 9% silicon that is metallurgically bonded to the stainless steel substrate. The hot dip coating process assures a tightly adherent, uniform coating on both sides of the product. A thin alloy layer readily permits normal forming practices without incurring significant damage to the coating. Aluminized Steel Type 1 Stainless 409 and 439 are currently available in a coating weight of 0.25 oz/ft2 minimum. A schematic drawing of a cross section is shown.

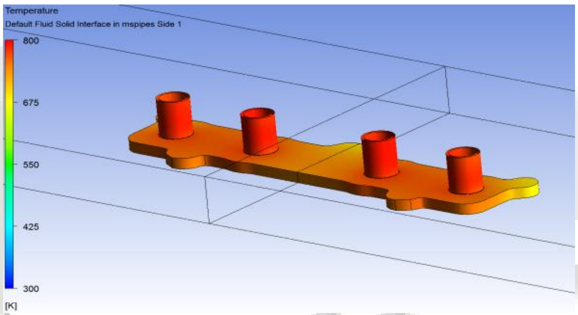

Fig. 9: Temperature Distribution of Exhaust Manifold With Aluminised Tubes and SS Flanges

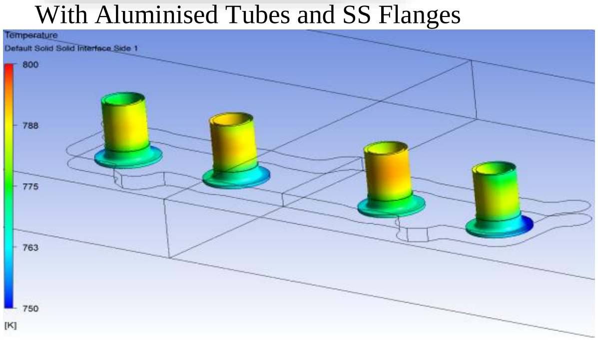

Fig. 10: Temperature Distributions of Aluminized Steel Pipes

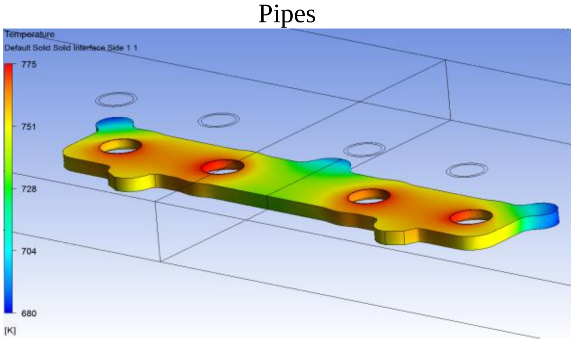

Fig. 11: Temperature Distribution of SS-316 Flange Material

In CFD all fluid zones like hot exhaust fluid and ambient air surrounding the manifold assembly obeys fluid dynamic theory. To study the parameters/variables inside the hot exhaust system where it is difficult to arrive with sensor and take data we use numerical

Software has been developed. The equations were solved using conversation of mass, conservation of momentum and conservation of energy for thermal equilibrium and after the convergency curves and post-processing the following results have been arrived at.

A detailed discussion of the same has been carried out in our results and discussion column which has been done for design betterment. The same was solved using K-Epsilon and near wall method and results have been obtained. They have also been compared .
From the following drawing temperature vector for hot and fluid and surrounding temperature can be demonstrated and the eating and the cooling properties of fluids through convection and conduction can be inferred.

Current work would have been much simpler, if we have a temperature profile boundaries on all wall surfaces for the amount of hot exhaust fluid in the manifold. Since we are not aware of temperature BC on the pipe surfaces, we need to solve CFD analysis in the fluid region as well as CHT for the thermal distribution on the solid portion. CFD solves fluid region and plots temperature boundaries on the solid surfaces. CHT has a two way coupling with the fluid and the solid interface.

IV. VELOCITY DISTRIBUTION

CHT solves mass, momentum (k and epp Turbulence models), energy for all the four domains simultaneously. Since all the unknown parameters are inter related, calculations have been proceeded with boundary conditions as well as initially guessed unknown values for a complete domain which has app 190000 cells in each iteration. For each iteration, it calculates temperature distribution on the solid region. Since both are dependent parameters, initially solid temperature is guessed and solves for the fluid region. Later it calculates the thermal distribution on the solid region and compares with the guessed value. Then the guess is corrected and again the loop is initiated. It repeats till guessed temperature and actual temperature become same.

From the velocity distribution curves we infer the following things. The velocity distribution of hot fluid and the velocity distribution of ambient air. By inferring all these properties a better design for the material can be laid out for development of weldless exhaust manifold flanges.

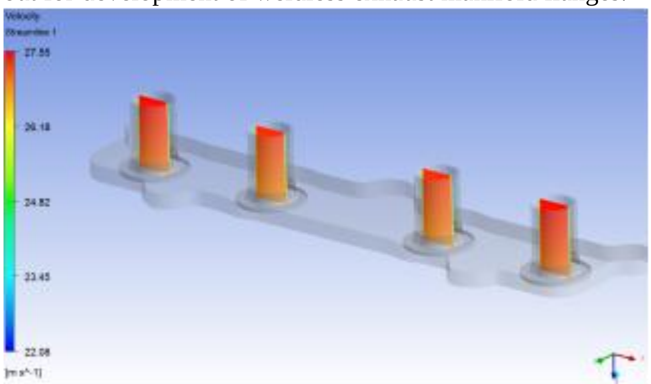

Fig. 12: Velocity Distribution of The Hot Fluid

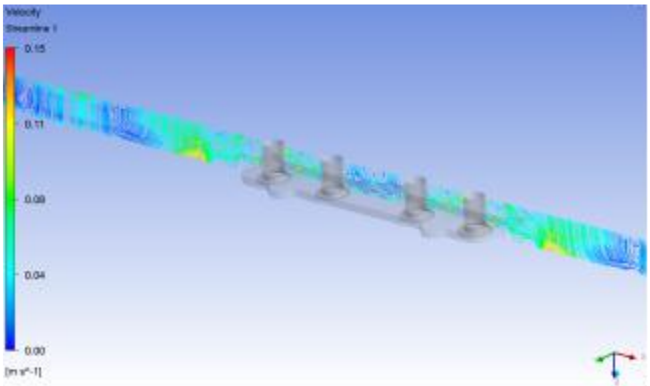

Fig. 13: Velocity Distribution of the Surrounding Air

V. THEORETICAL ANALYSIS

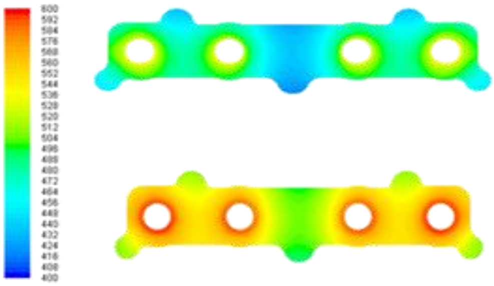

Fig. 14: Top: Pressure Fit Bottom: Welding Fit

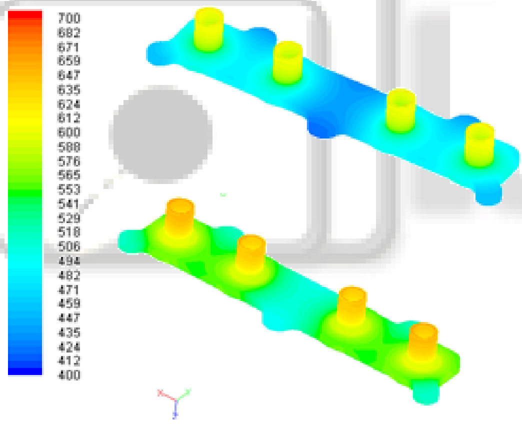

Fig. 15: Top: Pressure Fitting Bottom: Welding Fit

Theoretical Analysis of the existing model (Welding Joint) was carried out with the proposed model (press fit) with the application of proposed material properties for Aluminised Tubes and SS316 for flanges and the results have been arrived upon.

The static temperature distribution over two cases show that welding joint case has more thermal stresses (both on flange and pipes) than it's counterpart, press-fit joint. The press-fit joint formed with two different materials whereas, welding joint case is formed with three different material and each material has unique thermal properties, thus, thermal stresses are more in welding joint.

VI. CONCLUSIONS

Results infer that present approach is capable of perfectly predicting temperature distribution that may cause failure. The following are the results inferred:

The present analysis provides a few interesting results based on 2 model comparisons. In CHT analysis of both the models temperature distribution for model 2 (Analysis done with SS 316 Flange and Aluminised Tubes) showed better temperature distribution that may cause uneven volume coefficient of expansion.

Since the proposed model doesn't require any high heat exposed welding technique it can be free from manufacturing defects.

The current design has got three different materials which would correspond to different volume coefficient that may lead to high thermal gradients. This may lead to major cracks or failure and this can be overcome by our proposed model 2.

Having listed all the above advantages the proposed model 2 design can be free from failures in terms of temperature. Also from the static temperature plots we conclude that since the variation of temperature distribution is minimum the life of the proposed model is much greater than the existing model.

Further investigations can be carried out to develop a robust design which can be used to match the life of the exhaust manifold to that of the vehicle.

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