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Investigating the Influence of Exhaust Gas Temperature on Exhaust Manifold Design for Environmental Sustainability

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Abstract
This study investigates the relationship between exhaust gas temperature and exhaust manifold design in the context of environmentally friendly vehicle solutions. Two 3D manifold designs for 4-cylinder engines were designed, with installation space, materials, and temperature differences all taken into account. We investigated their thermal performance using the ANSYS Thermal Transient Module. Design 1 demonstrated efficient heat transport at greater temperatures, but Design 2 demonstrated superior heat management. Although more research is needed, these findings have far-reaching implications for sustainable automotive engineering. Finally, this research emphasizes the importance of exhaust manifold design in achieving environmental sustainability in the automotive sector.

Keywords: Exhaust manifold, 3D modeling, Thermal analysis, ANSYS.

Introduction

The automotive industry is a significant battleground in the quest for environmental sustainability. As around the globe is concerned about air quality, climate change, and resource conservation grow, the need to reduce the environmental impact of cars becomes more pressing. One critical aspect of this endeavor is the efficient regulation of exhaust gas temperature, which has a significant impact on the design and performance of exhaust manifolds. With a steadfast dedication to increasing environmental sustainability in the automotive sector, this research digs into the subtle interplay between exhaust gas temperature and exhaust manifold design. Several compelling factors influenced our decision to pursue this research issue. First and foremost, the global automotive sector is under increasing pressure to reduce its environmental imprint by lowering emissions and improving fuel efficiency. The exhaust system is at the heart of these efforts, with the exhaust manifold playing a critical role in funneling exhaust gases from engine cylinders to the exhaust system. Understanding how exhaust gas temperature affects manifold design is critical for satisfying severe environmental criteria and increasing sustainability.

Our research has implications that transcend beyond the laboratory. Our findings have implications for both society and industry. We aim to contribute to the reduction of harmful emissions, decreased fuel consumption, and, ultimately, a cleaner and more sustainable environment by optimizing exhaust manifold design based on exhaust gas temperature dynamics. In the industrial context, our research findings can help to inform the development of more efficient and ecologically friendly exhaust systems for automobiles, which will help to meet global sustainability goals. We have set precise goals and objectives to drive our research. We intend to create a thorough 3D model that includes two distinct types of exhaust manifold designs. We will assess the thermal performance of different manifold designs under varying exhaust gas temperature circumstances using transient thermal analysis. We will also calculate the overall heat flux experienced by the exhaust manifolds throughout operational cycles.

Our drive stems from a strong desire to advance sustainable practices in the automobile industry. We are motivated by the realization that novel methods for exhaust manifold design, based on the complex interaction of exhaust gas temperature, have the potential to significantly reduce emissions and resource consumption. We hope to play an important role in the creation of cleaner, more efficient automobiles through our research, fostering a healthier Earth for future generations. We introduce various new dimensions in this study project. We begin an investigation into how exhaust gas temperature affects exhaust manifold design, a facet that has remained largely unexplored in the pursuit of environmental sustainability by automobile engineering. We construct accurate renderings of two distinct exhaust manifold designs using modern 3D modeling techniques. We get insights into how these systems function under dynamic settings, allowing for the varying temperatures of exhaust gases, by transient thermal analysis. In addition, we compute and examine the total heat flux experienced by the exhaust manifolds, providing essential data for optimizing their thermal efficiency.

Literature Review

A complete thermo-mechanical analysis approach for exhaust manifolds in four-stroke automotive Diesel engines is described in the study authored by Höschler et. al[1]. On the hot gas side, the primary focus is on appropriately characterizing transient heat transfer events. The authors present a new method for calculating quasi-steady-state heat transfer and gas temperature profiles within a manifold that combines a 1-dimensional exhaust gas flow model with a 3-dimensional finite element thermal analysis. The analysis also includes correction variables to account for the engine's operational characteristics, providing a detailed understanding of local heat transfer variances. Notably, the paper investigates the impact of transient considerations on component stress-strain states, indicating that peak stresses occur during transient states rather than under full load conditions. This discovery emphasizes the importance of transient peak stress, strain range, and peak temperature in determining the fatigue life of a component using suitable fatigue data.

The fundamental goal of Ahmad et. al[2] research is to undertake a thermo-mechanical examination of a tractor exhaust manifold, with a focus on its response to elevated temperatures. The study entails evaluating the Finite Element Analysis (FEA) simulation findings while accounting for heat impacts. The fundamental frequencies of the exhaust manifold are determined using modal analysis, which is based on free vibrations. A solid model of the exhaust manifold is created in Pro-E, and finite element analysis is performed in Ansys 14.5. A constant exhaust gas temperature of 800 °C is applied to the manifold as a simulation parameter. The modal analysis provides important insights into the natural frequencies of vibration, which range from 53.2 to 466.68 Hz, and provides vital information on the vibration properties of the exhaust manifold.

The study by Chen et. al[3] introduces a CAE analytical approach for evaluating the exhaust manifold design of a turbocharged petrol engine. This method aids in the early discovery of structural flaws and the diagnosis of failures. The work used transient nonlinear finite element analysis to assess plastic deformation and thermal-mechanical behavior during thermal shock cycles in a variety of engine situations. Thermal boundary conditions are provided using transient heat transfer simulations. The model contains manifold components, and the findings show that cracking and exhaust leakage are caused by plastic deformation and manifold flange distortion. The study's adjustments met guideline boundaries, assuring long-term viability. The report finishes with useful exhaust manifold design recommendations. Using transient nonlinear finite element analysis, Delprete et. al[4] study the thermo-structural behavior of two cast iron commercial exhaust manifolds. There are two FEA models used: one considers manifold interaction with gaskets, cylinder head, fastener pretension, and geometry limitations, while the other only considers the manifold. The research looks at heat exchange interfaces, thermal assessments, and stress-strain profiles. Notably, the computational results agree with the experimental data, which improves our understanding of the thermal performance of these exhaust manifold components.

A Sequential Coupled heat-structural Analysis technique is used in this study by Jain et. al[5] to analyze heat stresses and deformations under settings that closely resemble real-world operational scenarios. The study includes a variety of materials, including cast iron and structural steel, and is carried out under reference environmental testing circumstances with varying ambient temperatures. For finite element analysis, ANSYS Workbench 14.0 is used, which allows for the calculation of linear steady-state temperature distributions and subsequent structural analysis. Thermal analysis determines temperature distributions in an exhaust manifold, whereas structural analysis computes deformation, stress, and strain using thermal inputs. The purpose of this analysis is to determine the suitability of materials for the specified exhaust manifold design in terms of serviceability. The article offers and discusses the investigation's primary findings and details.

The research done by Eroglu et. al[6] delves into the examination of three distinct CAE (Computer-Aided Engineering) approaches and techniques used for simulating fluid flow within an exhaust manifold, especially given the challenging pulsating nature of this flow in internal combustion engines. Experiments on manifold temperatures were carried out to validate the efficacy of each strategy. These projected metal temperatures are then used for thermo-structural durability analysis, which is beyond the scope of the study. Finally, the study hopes to shed light on the feasibility and accuracy of CAE approaches for simulating exhaust manifold fluid flow and heat distribution.

The study investigates the integration of temperature distribution from Computational Fluid Dynamics (CFD) into thermal-stress studies in the paper authored by Fan et. al[7]. A CFD software based on the Finite Volume Method (FVM) is used, together with a hybrid mesh and node-based variables. Because of this compatibility, temperature distribution and mesh can be used directly in thermal stress analysis. Three approaches are investigated: 1) applying the CFD mesh and temperature distribution directly, 2) separate fluid and solid region calculations with interpolation, suitable for large-scale models, and 3) interpolation of the CFD temperature field to Finite Element Method (FEM) mesh nodes for structural analysis temperature mapping. This study sheds light on the benefits of combining CFD and FEM for complete thermal-stress analysis.

The primary focus of Gocmez et. al[8] article is on two key aspects: first, establishing a reliable approach to forecast exhaust manifold failures, including TMF cracks, vibration concerns, and gasket problems. Second, the research investigates design optimization to eliminate structural flaws. It examines both human and automatic optimization approaches, emphasizing the benefits and drawbacks of each. While automatic shape optimization speeds up development, it necessitates technical expertise and clear problem definition. Due to production restrictions, the study also emphasizes the necessity for specialized optimization methodologies for casting and manufactured manifolds. The study provides high-accuracy failure prediction and presents an optimization tool for addressing structural deficiencies in substantially stressed exhaust manifolds.

Kawano et. al[9] present a complete analysis of an exhaust manifold subjected to nonlinear thermal deformation in this study. To improve computational accuracy, the work applies a Thermal Elasto-Plastic finite element model that incorporates creep strain, temperature-dependent apparent strain, and a nonlinear stress-strain relationship. Geometry is discretized using three-dimensional solid and shell isoparametric elements, and boundary nodes near the cylinder head-exhaust manifold interface are supported by three-way springs, allowing movement in three-dimensional coordinates. The model is validated experimentally, revealing high agreement between the model and actual data in both temperature and strain distributions. This emphasizes the importance of taking creep strain into account in exhaust manifold thermal deformation calculations.

Mamiya et. al[10] describe a unique method for assessing temperature distribution and estimating thermal fatigue life in engine exhaust manifolds during the early design phases that combines computational fluid dynamics (CFD) and finite element (FE) analysis. This method takes into account both external and internal flow fields and makes use of digital mock-ups of the vehicle and engine. The study correctly predicts temperature distribution and thermal fatigue life, with experimental data closely matching. This method provides an effective way to improve exhaust manifold design quality while decreasing development time and expenses.

The impact of fin attachment on lowering thermal stress in the exhaust manifold of an off-road diesel engine, specifically the Komatsu HD325-6, is investigated in a study conducted by Partoaa et. al[11]. A combined thermo-fluid-solid analysis is used to thoroughly analyze the thermal behavior of the manifold, including thermal flow, thermal stress, and thermal deformation. The research entails simulating flow within the manifold and analyzing parameters including velocity, pressure, and temperature. These flow parameters are then incorporated into a solid model in order to determine thermal stresses and deformations under a variety of operating situations. According to the findings, a combination of improvements, such as increasing shell thickness and adding fins, can lower thermal stresses by up to 28%, with the fin attachment playing a substantial part in this stress reduction. This study adds to our understanding of how to improve the performance and longevity of exhaust manifolds in off-road diesel engines.

Sangamesh et. al[12] focus on modeling and comparing the performance of multi-end exhaust manifolds to single-end counterparts in this study. The finite element approach is used for both structural and thermal evaluations. Furthermore, the structural and thermal behavior of various materials, such as mild steel, cast iron, stainless steel, and medium carbon steel, is evaluated. The findings show that multi-end exhaust manifolds have better stress and temperature distribution than single-end counterparts, with stress values 20 MPa lower. The study does observe, however, that changing materials has only a minor effect on stress and temperature distribution in the manifolds. This study sheds light on manifold design and material selection for optimal performance.

In this work, Shimizu et al. [13] present a new computer code developed to analyze heat conduction in structures with complex shapes, taking into account heat flow coupling. The code differs in that it uses the Finite Volume Method (FVM) to discretize the fluid domain and the Finite Element Method (FEM) to discretize the solid domain. The study dives into the origins of the code and shows how it can be used in practice for exhaust duct thermal conductivity analysis. It is an important engine component with a complex geometry and the need to deal with the interaction of the heat flow with the duct material.

Sissa et. al[14] present a study aimed at estimating the fatigue life of the exhaust manifold of a turbocharged Diesel engine. A thermo-structural analysis is used in the first part of the study to investigate low-cycle thermal fatigue caused by temperature changes, and dynamic harmonic analysis is used in the second half to analyze high-cycle fatigue caused by engine vibrations. The methodology uses these findings to calculate fatigue life using the Dang Van fatigue criterion. The study sheds light on both low-cycle and high-cycle fatigue events in exhaust manifold components, providing a thorough understanding of their endurance under thermal and vibrational loads.

The focus of Valarmathi et. al[15] research is on thermal stress-induced flaws in exhaust manifolds caused by the collection and conveyance of waste gases. To address these concerns, the study investigates the use of various ceramic coatings on the manifold surface. CATIA is used to create 3D models of both coated and uncoated manifolds, which are then thermally analyzed using ANSYS software and the finite element technique. This study sheds light on the possible benefits of ceramic coatings in reducing faults and increasing exhaust manifold performance.

Methodology

 Design 1	 Design 2

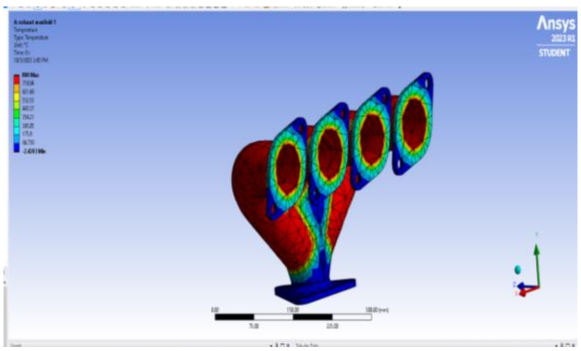
Figure 1: Various designs of Exhaust manifold

A systematic research technique was rigorously followed in our attempt to investigate the key relationship between exhaust gas temperature and exhaust manifold design for the development of environmental sustainability. Our designs were thoughtfully crafted, beginning with the conceptualization of two distinct 3D models, specially tailored to accommodate 4-cylinder engines. We took into account the constraints of available installation space, material availability, exhaust gas discharge rates, and exhaust gas temperatures. The elaborate drawings were then painstakingly turned into exact 3D models using Autodesk Fusion 360, providing the highest level of accuracy in portrayal. These precisely built 3D models were then sent in STEP file format to the ANSYS Thermal Transient Module, a specialized environment designed to analyze transient thermal phenomena. The mesh generation process began here, with a carefully tuned mesh produced with unwavering attention to orthogonal quality and aspect ratios. This mesh helps to precisely capture the complicated geometry of the exhaust manifold models.

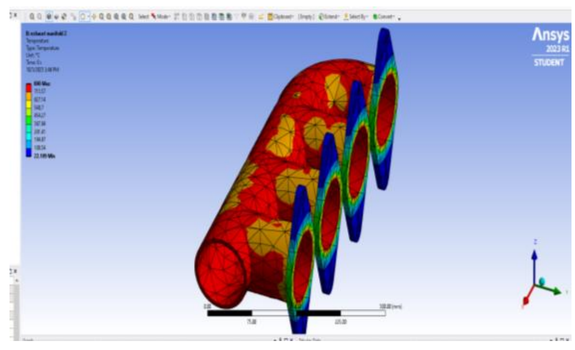
The temperature parameters were carefully determined with the projected temperature dispersion within the collectors under various operation scenarios in mind. These assignments serve as a foundation for future thermal research. We evaluate the thermal conductivities of collector materials by modeling the intricate dance of heat diffusion along the collector's walls and surfaces using the basic principles of heat transfer. The components for results analysis and visualization were meticulously designed. These modules, which comprise general temperature distribution and heat flow distribution, aid in comprehending how temperature and heat spread on various surfaces.

In conclusion, our research methodology combines advanced 3D modeling techniques with comprehensive computational analysis to shed light on the complex interaction between exhaust gas temperature and exhaust manifold design. Our study aspires to provide invaluable insights that will empower the development of more efficient and environmentally sustainable exhaust systems within the automotive industry, thus contributing to the global drive for a cleaner and greener future by meticulously simulating conductive heat transfer within the manifold models.

Result and Discussion



Design 1



Design 2

Figure 2: Temperature Distribution along the surface of the Exhaust manifold

Figure 2 shows the temperature distribution along the surface of the exhaust manifold. Design 1 shows higher temperatures along the surfaces compared to Design 2. It also shows that due to complications of manufacturing Design 1 has uneven temperature distribution on the inner and outer sides, whereas Design 2 has better temperature distribution along the surface.

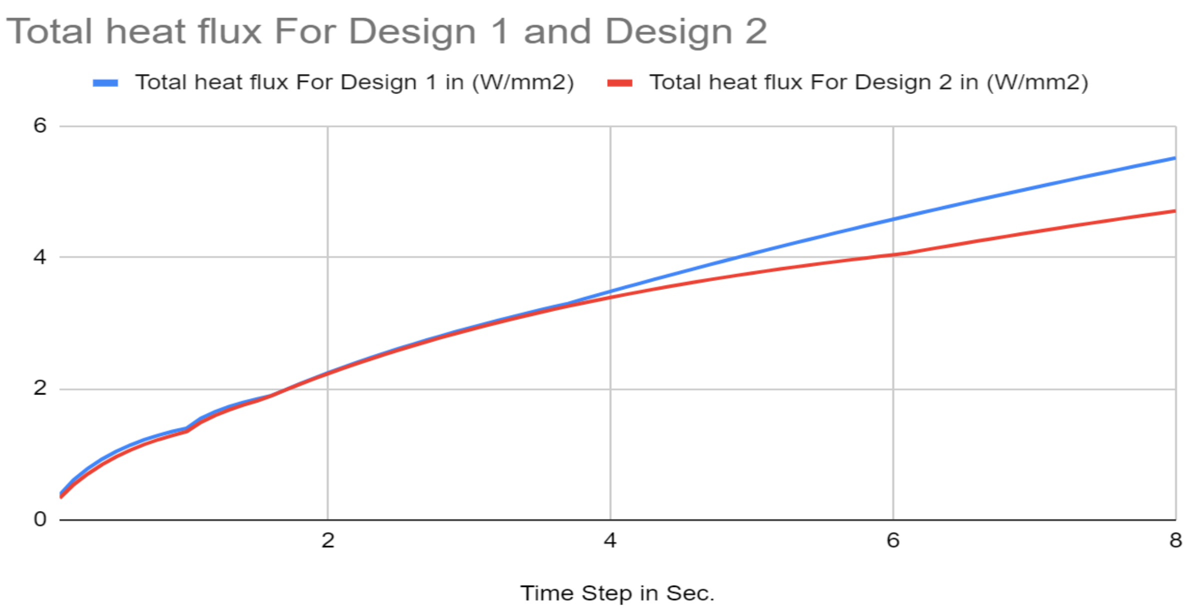


Figure 3: Heat Flux distribution along the surface of both the Exhaust manifold Design.

The data in Figure 3 shows a thorough examination of the temporal fluctuations in total heat flux for two separate manifold designs, Design 1 and Design 2. These findings provide insight into the thermal behavior of exhaust manifolds under various situations.

For Design 1, the total heat flux exhibited a constant rising trajectory throughout time. It gradually increased from 0.38172 W/mm2 to 5.5133 W/mm2 after 8 seconds of simulation, with a time step of 0.1 seconds. This pattern implies that Design 1 has strong thermal performance, exhibiting its ability to properly handle growing heat flux. Design 2, on the other hand, displayed a similar but distinct design. The total heat flow began at 0.33227 W/mm2 with a time step of 0.1 seconds and steadily increased to 4.708 W/mm2 at the end of the 8-second simulation period. While Design 2 likewise demonstrated excellent thermal endurance, it had a significantly lower heat flux than Design 1. The comparison of these results highlights critical factors for exhaust manifold design. Throughout the experiment, Design 1 maintained a greater overall heat flux, indicating the possibility for more efficient heat transmission. This property can be useful in applications where controlling higher exhaust gas temperatures and lowering emissions are critical. While Design 2 demonstrated strong thermal performance, it had a reduced overall heat flux. This suggests that it may be more suitable for circumstances requiring excellent heat management and dissipation.

Conclusion

To promote environmental sustainability in the automotive industry, our research explores the complex interplay between exhaust gas temperature and exhaust manifold design. Using a systematic approach that included 3D modeling, and and transient thermal analysis, we obtained significant insights into the thermal behavior of two different collector designs, Design 1 and Design 2. These results have important implications for the development of a more efficient and ecological model. friendly exhausts that contribute to a cleaner and greener automotive future.
Our study found compelling temporal trends in total heat flux for both arrangements. Model 1 showed consistently higher heat flow values during the simulation, indicating the possibility of more efficient heat transfer systems. This feature can be useful in situations where higher exhaust gas temperatures and lower pollution are required. Design 2, on the other hand, had a significantly lower overall heat flux despite excellent heat resistance. As a result, it can be an excellent choice for thermal regulation and vaporization applications.
However, we recognize that this is preliminary research. Future tests should be more comprehensive, taking into account material properties, structural integrity, and fluid dynamics in the exhaust system. Real-world testing and validation are also needed to ensure that our results can be used in practice.

Reference

1. Höschler, K., J. Bischof, and W. Koschel. "Thermo-mechanical analysis of an automotive diesel engine exhaust manifold." *European Structural Integrity Society*. Vol. 29. Elsevier, 2002. 299-308.
2. Ahmad, Faraz, et al. "FEA Simulation Based Thermo-mechanical Analysis of Tractor Exhaust Manifold." *CAD/CAM, Robotics and Factories of the Future: Proceedings of the 28th International Conference on CARs & FoF 2016*. Springer India, 2016.
3. Chen, Ming, et al. "Design of the Exhaust Manifold of a Turbo Charged Gasoline Engine Based on a Transient Thermal Mechanical Analysis Approach." *SAE International Journal of Engines* 8.1 (2015): 75-81.
4. Delprete, Cristiana, and Carlo Rosso. *Exhaust manifold thermo-structural simulation methodology*. No. 2005-01-1076. SAE Technical Paper, 2005.
5. Jain, Sweta, and AlkaBani Agrawal. "Coupled Thermal-Structural Finite Element Analysis for Exhaust Manifold of an Off-Road Vehicle Diesel Engine." *International Journal of Soft Computing and Engineering (IJSCE)* 3 (2013): 226-223.
6. Eroglu, Sinan, et al. *Thermal analysis of heavy duty engine exhaust manifold using cfd*. No. 2016-01-0648. SAE Technical Paper, 2016.
7. Fan, Qin Yin, Masayuki Kuba, and Junichi Nakanishi. *Coupled analysis of thermal flow and thermal stress of an engine exhaust manifold*. No. 2004-01-1345. SAE Technical Paper, 2004.
8. Gocmez, Taner, and Udo Deuster. *An integral engineering solution for design of exhaust manifolds*. No. 2009-01-1229. SAE Technical Paper, 2009.
9. Kawano, Hiroaki, et al. *Improvement in the thermal elasto-plastic FEM model applied to exhaust manifold*. No. 911771. SAE technical paper, 1991.
10. Mamiya, Naohisa, Takafumi Masuda, and Yasushi Noda. *Thermal fatigue life of exhaust manifolds predicted by simulation*. No. 2002-01-0854. SAE Technical Paper, 2002.
11. Partoaa, Ali Akbar, Morteza Abdolzadeh, and Masoud Rezaeizadeh. "Effect of fin attachment on thermal stress reduction of exhaust manifold of an off road diesel engine." *Journal of Central South University* 24 (2017): 546-559.

12. Sangamesh, R., et al. "Modelling of single and multi-port manifolds and studying the influence of structural and thermal behaviour on exhaust manifolds used in automotive applications." *International Journal on Interactive Design and Manufacturing (IJIDeM)* (2022): 1-10.
13. Shimizu, Tatsuya, and Masahiko Ohtani. "Numerical simulation of heat transfer and fluid flow applied to exhaust manifold." *JSAE review* 17.1 (1996): 17-23.
14. Sissa, Simone, Matteo Giacopini, and Roberto Rosi. "Low-cycle thermal fatigue and high-cycle vibration fatigue life estimation of a diesel engine exhaust manifold." *Procedia Engineering* 74 (2014): 105-112.
15. Valarmathi, T. N., et al. "Design and thermal analysis of coated and uncoated exhaust manifold." *International Journal of Ambient Energy* 41.2 (2020): 157-160.