TÜRKİYE CUMHURİYETİ
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
MECHANICAL ENGINEERING DEPARTMENT

INVESTIGATION OF THE THERMAL STRESSES OF THE EXHAUST MANIFOLD IN THE ENGINE OPERATING UNDER DIFFERENT CONDITIONS

ÖMER CERYAN

M.Sc.

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THESIS ADVISOR
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ADANA, 2023

ÖZET

FARKLI ŞARTLAR ALTINDA ÇALIŞAN MOTORDAKİ EGZOZ MANİFOLDUNUN ISIL GERİLMELERİNİN İNCELENMESİ

Ömer CERYAN

Yüksek Lisans, Makine MühendisliğiAnabilim Dalı
Danışman: Doç. Dr. Gökhan TÜCCAR
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Geçmişten günümüze motor teknolojisindeki gelişmeler ve artan ihtiyaçlar nedeniyle içten yanmalı motorlardan talep edilen güç, verim ve çeşitliliğin artmasını beraberinde getirmektedir. Bu beklentilerin karşılanması, bu parametreleri yakından ilgilendiren aksamlarının tasarımında ve üretiminde yapılacak iyileştirmelerle mümkün olacaktır. Egzoz sistemi, motorun performansı, yakıt tüketimi, motor gücü ve kullanım konforu ile yakından ilgilidir.

Bu tez çalışmasında, çeşitli koşullar altında çalışan turbo şarjlı bir benzinli motorun egzoz manifoldunun tasarımını değerlendirmek için bir CAE analiz yaklaşımı açıklanmaktadır. Tasarlanan manifold için motorun nominal hız tam yük ve rolanti hızı koşullardaki şartlarını içeren termal şok döngüleri sırasında egzoz manifoldunda meydana gelebilecek olan deformasyonlar ve maknik davranışlar geçici doğrusal olmayan bir sonlu eleman yöntemi kullanılarak sümüle edilmiştir. Sonlu eleman modeli, silindir kafası, egzoz manifoldu, turbo şarj ve cıvataları içerir. Daha önceki çalışmalar ışığında simülasyonlardan önce muhtemel çatlak konumları ve termal gerinimlere yoğunlukla maruz kalabilecek olan bölgeler tahmin edilerek bu bölgelere tasarım aşamasında malzeme yığılması ve takviye kalınlıklar eklenmiştir. Yapılan TMF analizleri sonucu yüksek sıcaklıklarda parçada oluşan ısıl gerilmeler parçanın yapısal özelliklerini bozmadığı saptandı ve egzoz manifoldu tüm testleri başarıyla geçti.

Anahtar Kelimeler: İçten yanmalı motor, egzoz manifoldu, sıcaklık dağılımı, sıcaklık tahmini, termal değerlendirme, ısı transferi, termo mekanik yorgunluk (TMF), hesaplamalı akışkanlar dinamiği (CFD).

ABSTRACT

INVESTIGATION OF THE THERMAL STRESSES OF THE EXHAUST MANIFOLD IN THE ENGINE OPERATING UNDER DIFFERENT CONDITIONS

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The power required from internal combustion engines has increased in efficiency and variety as a result of advances in engine technology and rising requirements from the past to the present. By making improvement to the design and manufacture of components that are directly connected to these criteria, it will be able to meet these expectations. The performance, fuel efficiency, power, and user-friendliness of the engine are all intimately correlated with the exhaust system.

This thesis describes a CAE analytical technique to assess the exhaust manifold design of a turbocharged gasoline engine running under diverse situations. Using a transient nonlinear finite element approach, deformations and mechanical behaviors that might develop in the exhaust manifold throughout thermal shock cycles, including engine rated speed, full load, and idle speed circumstances, are simulated for the specified manifold. The turbocharger, exhaust manifold, cylinder head, and bolts are all included in the finite element model.

Prior to the simulations, potential fracture sites and places that would be significantly exposed to heat stresses were evaluated in light of prior research, and during the design stage, material agglomeration and reinforcing thicknesses were added to these regions. The TMF analyses showed that the thermal stresses on the component at high temperatures did not degrade the part's structural characteristics, and the exhaust manifold passed all tests with flying colors.

Keywords: Internal combustion engine, exhaust manifold, temperature distribution, temperature prediction, thermal assessment, heat transfer, thermo mechanical fatigue (TMF), computational fluid dynamics (CFD).

Dedication

to my precious family

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Once and for all, I would want to express my gratitude to my very loving wife Suzan Akgün Ceryan for her support and for being there for me during the entire procedure.

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Ömer Ceryan

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BC	: Boundary condition
BDC	: Bottom Dead Center
C	: Celsius
CA	: Crank Angle
CAE	: Computer Aided Engineering
CCM	: Central Control Module
CFD	: Computational Fluid Dynamics
CI	: Compression Ignition
DOC	: Diesel Oxydation Catalyst
DPF	: Diesel Partial Filter
EGR	: Exhaust Gas Recirculation
FEA	: Finite Element Analysis
HiSiMo	: High Silicon and Molybdenum Content
HTC	: Heat Transfer Coefficient
ICE	: Internal Combustion Engine
LBSE	: Long Bend Side Exit
LBME	: Long Bend Middle Exit
LCF	: Low Cycle Fatigue
M	: Metric
MPa	: Megapascal.
PEEQ	: Equivalent Plastic Strain
RANS	: Reynold Navier Stokes
mRe	: Reynold Number
RPM	: Revolutions per Minute
SCR	: Selective Catalyst Reduction
SI	: Spark Ignition
TDC	: Top Dead Center
TMF	: Thermomechanical Fatigue

1. INTRODUCTION

Internal combustion engines need air while they are running, and for them to work properly, the waste gases produced during operation must be thrown out. There are systems that control the air flow in the vehicles, allowing the air to enter the engine and throw out the polluted gas. Developments in today's engine technology and the increase in power demanded from internal combustion engines show parallelism. Accordingly, regulations on emissions are increasing. In particular, emission efficiency and fuel consumption depend on the design of the exhaust manifold.

The exhaust manifold is an essential element of an engine that's responsible for collecting the exhaust gases from the engine's cylinders and directing them to the exhaust system. While venting occurs, the manifold is exposed to high temperatures and thermal stresses that can cause damage and failure. In this study, the thermal stresses of the exhaust manifold in an engine operating under different conditions will be discussed.

When the engine is operating under normal conditions, the exhaust manifold is subordinated to high temperatures due to the hot gases flowing through it. The temperature of the exhaust gases can reach up to 900 °C or advanced, depending on the engine's operating conditions. At similar high temperatures, the exhaust manifold undergoes thermal expansion, which can lead to stress and distortion of the manifold.

Also, the exhaust gases can produce thermal slants within the exhaust manifold, which can lead to discrimination, expansion and warping of the manifold. This warping can beget the manifold to come misaligned, leading to leaks and reduced engine performance.

Under high-performance conditions, similar as racing or towing heavy loads, the engine produces further heat and pressure, performing in advanced exhaust gas temperatures and inflow rates. This can further increase the thermal stresses on the exhaust manifold, leading to more significant distortion and warping.

There are also several factors that can contribute to increased thermal stresses on the exhaust manifold, including indecorous tuning, machine misfires, and congested catalytic transformers. These issues can beget the engine to run hotter, performing in advanced exhaust gas temperatures and inflow rates, which can lead to increased thermal stresses on the manifold.

Indecorous tuning can create the engine to run spare, which means that it’s entering too little energy and too important air. This causes the engine to run hotter, performing in advanced exhaust gas temperatures and inflow rates. A miscarrying cylinder can also cause the exhaust gases to be hotter and further concentrated, leading to increased thermal stresses on the manifold.

Congested catalytic transformers can also contribute to increased thermal stresses on the manifold. When the engine is congested, the exhaust gases cannot flow freely, causing them to back up and increase in temperature. This can lead to increased thermal stresses on the manifold and other exhaust factors.

It's also worth noting that aftermarket variations to the engine can increase thermal stresses on the exhaust manifold. For illustration, adding a turbocharger or supercharger can increase the engine's power affair but also increases the temperature and inflow rate of the exhaust gases. This can affect in increased thermal stresses on the manifold and other exhaust factors, leading to implicit failure or reduced lifetime of the exhaust system.

To alleviate the thermal stresses on the exhaust manifold, manufacturers use accoutrements that can repel high temperatures, such as cast iron, stainless steel, and ceramics. Also, some manufacturers use heat shields to cover the manifold from inordinate heat and reduce the temperature differential between the manifold and other engine factors.

Regular conservation of the exhaust system, including the manifold, can help inordinate thermal stresses and protract the manifold’s lifetime. This includes checking for leaks, examining the manifold for signs of distortion or warping, and replacing the multifarious gasket when necessary.

In conclusion, the exhaust manifold is an essential element of an engine that's exposed to high temperatures and thermal stresses during normal and high- performance operations. Manufacturers use accoutrements that can repel high temperatures and heat securities to alleviate these stresses. Regular conservation of the exhaust system can help damage and protract the manifold’s lifetime.

1.1. Internal Combustion Engine Working Principles

Internal combustion engines have been around for over a century and have played a significant part in the development of ultramodern society. They're extensively used in a variety of operations, including transportation, power generation, and artificial processes. The four and two-stroke cycle engines are the most generally used type of engine moment.

The internal combustion engine is a type of heat engine that converts the chemical energy stored in energy into mechanical energy. The first internal combustion engine was developed in the late 19th century, and since also, they've experienced significant advancements, performing in advanced effectiveness, lower emigrations, and bettered performance.

Internal combustion engines can be classified in several different ways. There are two main types of internal combustion engines spark- ignition (SI) engines and compression-ignition (CI) engines. SI engines are generally used in passenger buses, while CI engines are used in heavy-duty vehicles and artificial operations.

The four stroke cycle engines, which are the most common type of SI engine. The four-stroke cycle engine, also known as the Otto cycle engine, was constructed by Nikolaus Otto in 1867. It consists of four strokes intake, compression, combustion, and exhaust.(B. Heywood, 1988)

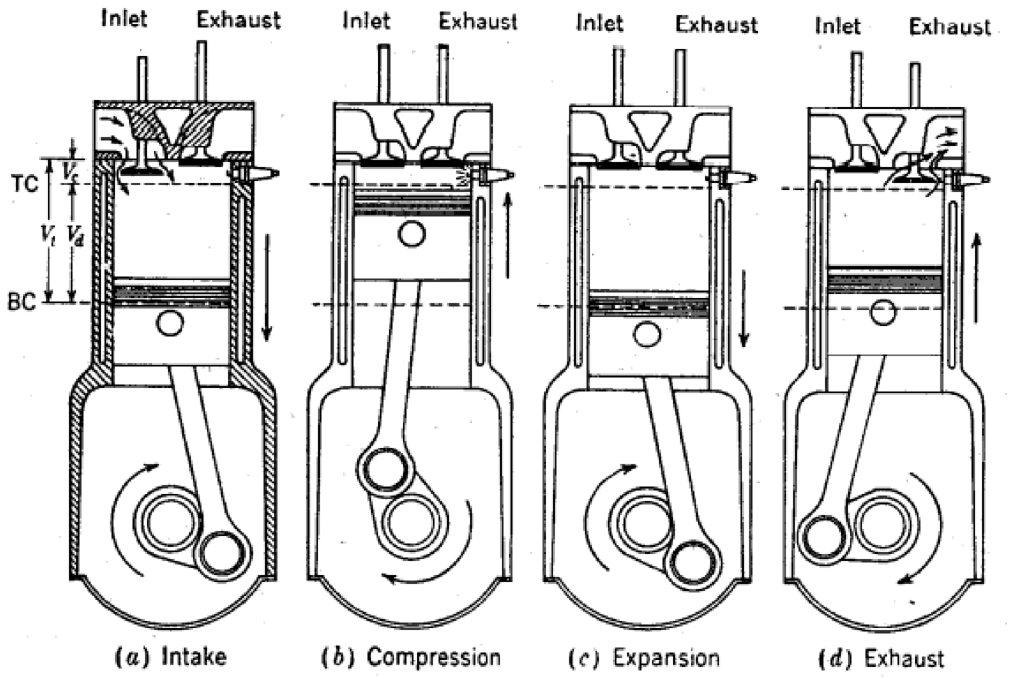

Figure 1.1. Four Stroke Engine Operating Cycle (B. Heywood, 1988)

The engine's operation begins with the intake stroke, where the piston moves down, creating a vacuum that draws in the air-energy admixture from the carburetor or energy injection system. The air-energy admixture enters the engine through the input stopcock, which is open during the intake stroke.

During the compression stroke, the piston moves up, compressing the air-energy admixture to high pressure and temperature. This compression raises the admixture's temperature to the point where it can enkindle when the spark draws fires.

The compression stroke is followed by the power stroke, where the spark draw ignites the air-energy admixture, creating a controlled explosion that drives the piston down, producing mechanical energy.

After the power stroke, the exhaust stroke begins, where the piston moves up, pushing the burnt gases out of the engine through the exhaust stopcock, which is open during this stroke. The four strokes of the engine are completed, and the cycle starts again.

In addition to the four-stroke cycle engine, there are other types of ICEs, including the two-stroke cycle engine, which is generally used in small engines similar to those set up in lawnmowers and chainsaws.

The two-stroke cycle engine operates on two strokes contraction and combustion/ exhaust, and it is less effective than the four-stroke cycle engine. At first stroke, very high pressure created by the combustion process forces the piston down in the power stroke. The expanding volume of the combustion chamber causes pressure and temperature to decrease as the piston travel towards bottom dead center (BDC). At the second stroke, all valves closed, the piston travels towards top dead center and compresses the air-fuel mixture to higher pressure and temperature. Near the end of the compression stroke, the spark plug is fired by the time the piston gets to top dead center (TDC), combustion occur, and next engine cycle begins.(W. Pulkrabek, 2003)

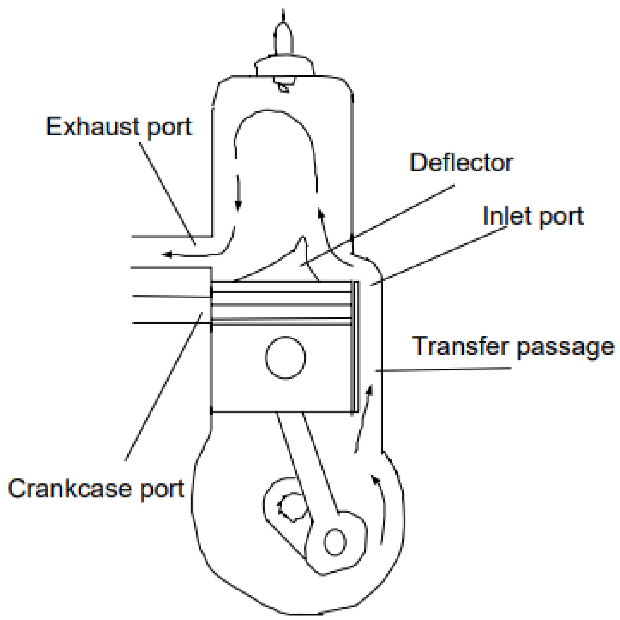

Figure 1.2. Two Stroke Engine Stroke Engine Operating Cycle (Salazar, 1998)

Internal combustion engines have been a driving force behind ultramodern society's development, and they continue to play a critical part in transportation, power generation, and artificial processes.

The most generally used engine is a four-stroke cycle engine. The engine's effectiveness, performance, and emigrations have been significantly better over time, making them a dependable and cost-effective source of power.

1.2. Exhaust System Definition

In this section, the components of the exhaust system will be introduced, and information will be given about its sub-components.

Vehicle exhaust systems are an essential part of ultramodern vehicles, designed to safely and efficiently remove dangerous gases and adulterants produced during the combustion of energy in the engine. The exhaust system has several crucial factors, each with a specific function, working together to control emigration and maintain the proper functioning of the vehicle.(Caterpillar, 2011)

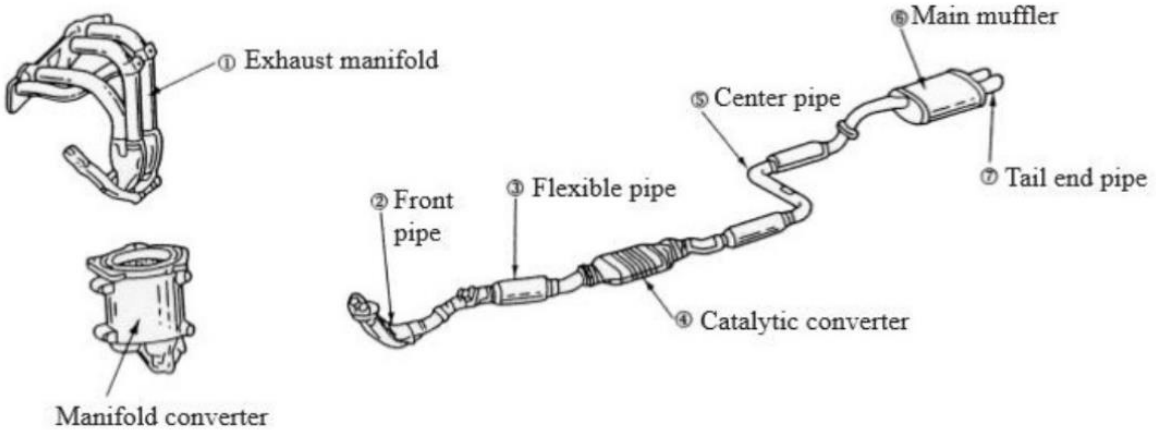

Figure 1.3. Exhaust System Schematic View (Betini et al., 2016)

The exhaust system starts from the exhaust valve (after the explosion time) and continues to the end of the exhaust pipe. A well-designed exhaust system is expected to fulfill the following important design criteria:

- To minimize the resistance to the gas flow and to keep the back pressure within the limits.
- Reducing exhaust emission values and providing legal emission values.

- To provide enough space between engine components and exhaust system components, to prevent parts from being affected by high temperature.
- Preventing the engine parts from working under high stress due to the weight of the turbocharger and exhaust manifold, thus ensuring longer life of the engine parts(Yalçındağ, 2018)

Exhaust system consists of exhaust manifold, supercharger or turbocharger, catalytic converter, exhaust gasket, exhaust pipes, mufflers and finally exhaust tips.

1.2.1. Exhaust Manifold

The exhaust manifold is the first element of the exhaust system and is responsible for collecting the hot gases produced during the combustion process in the engine's cylinders. The manifold is bolted to the engine block. Exhaust manifolds are typically made from cast iron, stainless steel, or stamped steel. Stainless steel is the most expensive because it doesn't rust and lasts very long, but steel pipe also gets points for good gas flow.

Exhaust gases collected in the manifold are released into the atmosphere in vehicles by first passing through the catalytic converter and then through similar structures such as the tailpipe muffler and exhaust tip. After the ends of each cylinder are joined in a single duct, the exhaust gases flow towards the base exhaust system and exit through the tailpipe.

1.2.2. Turbocharger

In internal combustion engines, chemical energy is converted into mechanical power as a result of the combustion event in the combustion chamber. Increasing the amount of clean air sent into the cylinder also means sending proportionally more fuel. As a result, the explosion pressure formed as a result of combustion is increased and the power obtained from the engine is also increased. Turbocharger is mainly used to increase the density and pressure of the air entering the cylinder. More air enters the engine compartment, making the air-fuel mixture more flammable, which creates more power and torque.

The turbocharger is connected to the exhaust line after the exhaust manifold. It basically consists of two impellers mounted on the same shaft. One of these wheels is the compressor and the other is the turbine. Overfilling is done with the help of the compressor wheel. Fresh air is sent to the combustion chamber under pressure by driving the compressor wheel. The drive of the compressor wheel comes from the exhaust gas formed as a result of the combustion reaction. (Yalçındağ, 2018)

1.2.3. Catalytic Converter

The catalytic converter is a pivotal part of the exhaust system, designed to reduce the dangerous emigrations produced by the engine. The converter is located between the exhaust manifold and the muffler and contains a catalyst, generally made of platinum, precaution, or rhodium, which reacts with the dangerous gases to convert them into lowe dangerous composites.

The catalytic converter, also known as the oxidation catalyst, contributes to the elimination of problems such as carbon monoxide, hydrocarbon, nitrous oxide-induced smog, and acid rain caused by the combustion of the air-fuel mixture. In this way, it plays an important role in protecting the environment and human health. Today, the catalytic converter is used in both diesel and gasoline cars. There are two types as two-way and three-way catalytic converter. Three-way catalytic converter: It renders carbon monoxide, hydrocarbons, and nitrogen oxides harmless. Two-way converters interact only with carbon monoxide and hydrocarbons.

1.2.4. Exhaust Pipe

The exhaust pipe is the section of the exhaust system that carries the gases from the engine to the catalytic converters and the muffler. The pipe is generally made of cast iron or stainless steel and is designed to repel high temperatures and erosion.

1.2.5. Muffler

The muffler is a critical element of the exhaust system, designed to reduce the noise produced by the engine and the exhaust gases. The muffler contains a series of chambers and baffles that help to dissipate the sound swells, reducing the noise position of the exhaust system.

The exhaust system, which operates at an extremely high pressure, expels the gases released in the engine with a high pressure. During the process of expelling the gases with high pressure, a great noise occurs.

In the muffler, which consists of partitions and tunnels the exhaust gas flow coming here is transferred from the first channel to another channel and its intensity is damped.

The gas, which comes to the muffler with high pressure and speed, continues its way with lower intensity and speed after the muffler.

1.2.6. Exhaust Tips

The exhaust tips are the visible part of the exhaust system and are located at the end of the exhaust pipe. The exhaust tips give the car a more powerful sound. However, normal nozzles usually have little effect on exhaust noise. Larger tips give the motor a more powerful, punchy sound, while smaller tips produce a harsher sound.

The tips are generally made of chrome or stainless steel and are designed to enhance the vehicle's appearance.

Summary exhaust system works by controlling the inflow of gases produced during the combustion process in the engine and filtering out dangerous emigrations before they're released into the atmosphere. The process begins with the exhaust manifold, which collects the hot gases produced by the engine's cylinders and directs them toward the catalytic converters.

The catalytic converter contains a catalyst that reacts with the dangerous gases, converting them into lower dangerous composites similar to carbon dioxide and water vapor. The engine is heated by the hot gases passing through it, which helps to spark the catalyst and increase its effectiveness.

The gases also flow through the exhaust pipe towards the muffler, which reduces the noise produced by the engine and the exhaust gases. The muffler contains chambers and baffles that dissipate the sound swells, reducing the noise position of the exhaust system.

Eventually, the gases exit the exhaust system through the exhaust tips, which enhance the vehicle's appearance and give a final outlet for the exhaust gases.

Vehicle exhaust systems play a critical part in controlling emigration and maintaining the proper functioning of the vehicle. The exhaust system consists of several crucial factors, each with a specific function, working together to safely and efficiently remove dangerous gases and adulterants produced during the combustion of energy in the engine. Advancements in technology and accouterment wisdom have led to significant advancements in the performance and effectiveness of vehicle exhaust systems, making them an essential part of ultramodern vehicles.

1.3. Importance and Working Principle of Exhaust Manifold

Vehicle exhaust systems are essential for the proper functioning of an engine. They play a critical part in controlling emigration and maintaining the proper functioning of the engine.

One of the crucial factors of the exhaust system is the exhaust manifold, which is mounted on cylinder head of an engine and responsible for collecting and directing the hot gases produced during the combustion process in the engine’s cylinders. In the Figure 1.4 is shown the schematic view of exhaust manifold disassembled from engine head.(Duman, 2016)

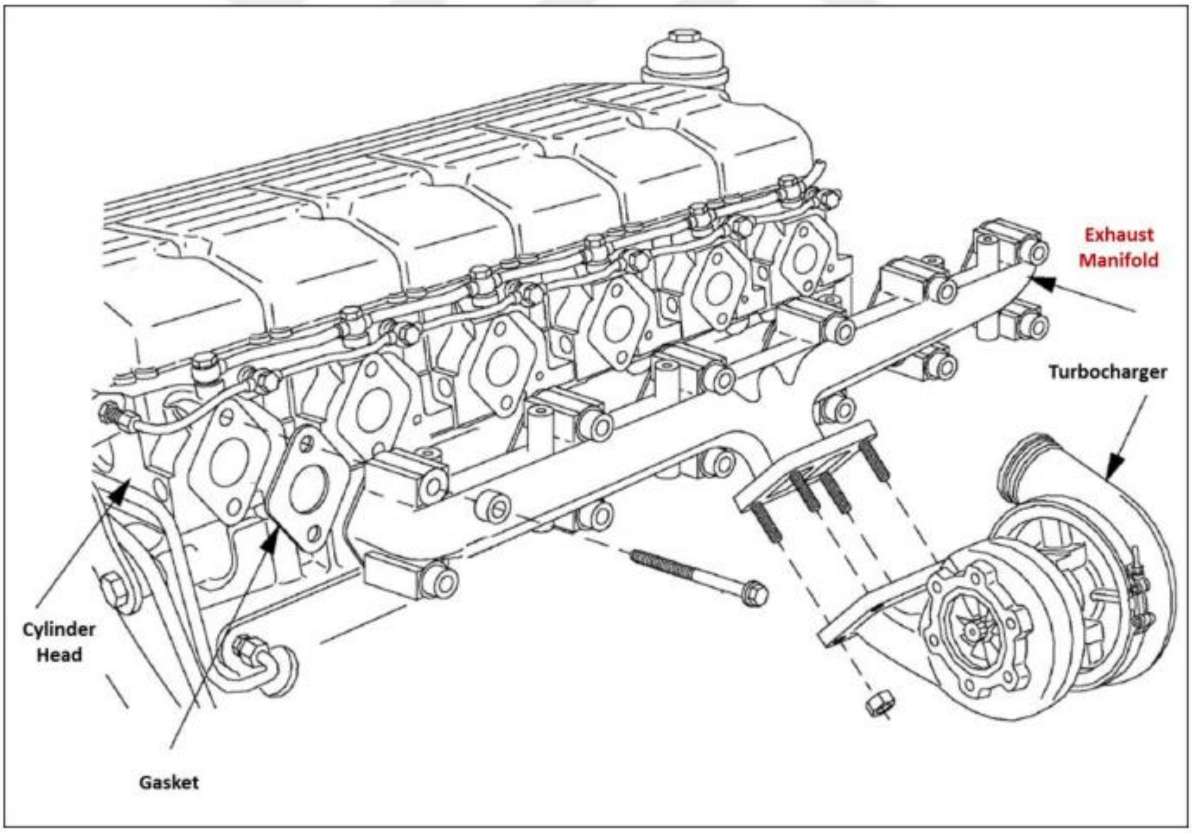

Figure 1.4. Engine Exhaust Manifold Schematic View (Duman, 2016)

The exhaust manifold is a pivotal element of the exhaust system, and its significance cannot be exaggerated. The manifold's primary function is to collect the hot gases produced during the combustion process in the engine's cylinders and direct them toward the catalytic converter.

The manifold's design is pivotal for optimizing engine performance, minimizing back pressure, reducing emigrations, and perfecting overall effectiveness.

A malfunctioning or inadequately designed manifold can lead to reduced engine performance, increased energy consumption, and implicit damage to other engine factors. therefore, icing that the manifold is designed and performing rightly is essential for the proper operation of the engine.

The manifold's shape and size are critical for optimizing engine performance. The manifold's pipes are designed to combine into a single outlet, which is connected to the exhaust pipe leading to the catalytic converter. The manifold's design is generally optimized for a specific engine, icing that the gases produced by the engine's cylinders are efficiently collected and directed toward the catalytic converter.

In conclusion, the exhaust manifold is a critical element of the exhaust system, responsible for collecting and directing the hot gases produced during the combustion process in the engine's cylinders. The manifold's design is pivotal for optimizing engine performance, minimizing back pressure, reducing emigrations, and perfecting overall effectiveness.

The manifold is generally made of cast iron, stainless steel, or ceramics designed to repel high temperatures and thermal stresses generated during the operation of the engine.

Advances in technology and equipment have led to significant improvements in the performance and effectiveness of vehicle exhaust systems, making them an essential part of state-of-the-art vehicles.

Overall, the exhaust manifold is an essential element of ultramodern vehicles, and its proper functioning is pivotal for the effective operation of the vehicle.

2. THEROTICAL FOUNDATION AND LITERATURE REVIEW

In the automotive engineering, exhaust manifold, which is mounted on cylinder head of an engine, collects the exhaust gas from the cylinders and dispose it to the exhaust after treatment system.

The exhaust manifold plays significant part in engine performance. Especially, exhaust emigration system effectiveness and energy consumption depend on multifarious design.

Currently, increase of engine performance and overall system effectiveness is the most struggling question seen in the automotive assiduity. During the engine operation, exhaust manifold is subordinated to severe thermal cycling under harsh working conditions, performing from high temperature exhaust gases, which also show transitory behavior. So, the automotive exhaust manifolds are designed and developed to supply minimal backpressure and turbulence and must be suitable to repel extreme heating under high temperature and cooling down under low temperature.

Exhaust manifold cracks from TMF are frequently seen on largely loaded engines. Due to cyclic thermal loads, thermo-mechanical fatigue cracks on exhaust manifold and gasket sealing failure are frequently observed during engine continuity tests, similar as thermal shock test.(Chen et al., 2014)

Thus, to come up with a robust and durable design is a grueling task. In early stages of the design process, advanced and robust CAE styles are needed for the durable design of exhaust manifolds.

The use of advanced simulation technologies enables the design and analyses masterminds to identify critical locales in an early phase of development and to meet measures to remove original structural sins. This minimizes the need for precious tackle testing, therefore reducing the overall product development cycle time and cost.(Gocmez et al., 2009)

Gocmez and Deuster concentrated on the development of a dependable approach to prognosticate failure of exhaust manifolds and on the elimination of structural failings through the optimization of design. The failure modes for TMF cracks, vibration and exhaust manifold gaskets are emphasized. This study demonstrated that a procedure for an integral result, which provides for the development of optimized exhaust manifolds that are failure-free. Accurate material and continuance modeling, when used in combination with correct representation of dominant loads and assembly constraints, enables dependable prognostications for the failure motion of exhaust manifolds.(Gocmez et al., 2009)

Chen describes a CAE analysis approach to evaluate the exhaust manifold design of a turbocharged gasoline engine at the current article. A nonlinear transient finite element method is used to calculate the plastic deformation and thermal mechanical behavior of the exhaust manifold assembly during thermal shock cycles. As a result of the simulation and the necessary basic calculations, it is stated that the necessary optimizations were made and the part passed the tests successfully.(Chen et al., 2014)

Zhi-En Liu and Xue-Ni Li realized the serial coupling of STAR- CCM and ABAQUS and give boundary conditions for the thermal fatigue analysis and while caried out transitory fluid-solid thermal coupling simulation by using the serial coupling system. Bi-directional fluid-solid coupling simulation between CFD software Star CCM and FEA software Abaqus was achieved, and transitory temperature and thermal stress distribution are attained. Also compared the thermal stress difference between the transitory and steady state computation. Results show that the difference of the temperature distribution is large and this effect the position of outside stress point on manifold. This study demonstrated that transitory analysis system is more effective to prognosticate thermal fatigue life of exhaust manifold.(Liu et al., 2013)

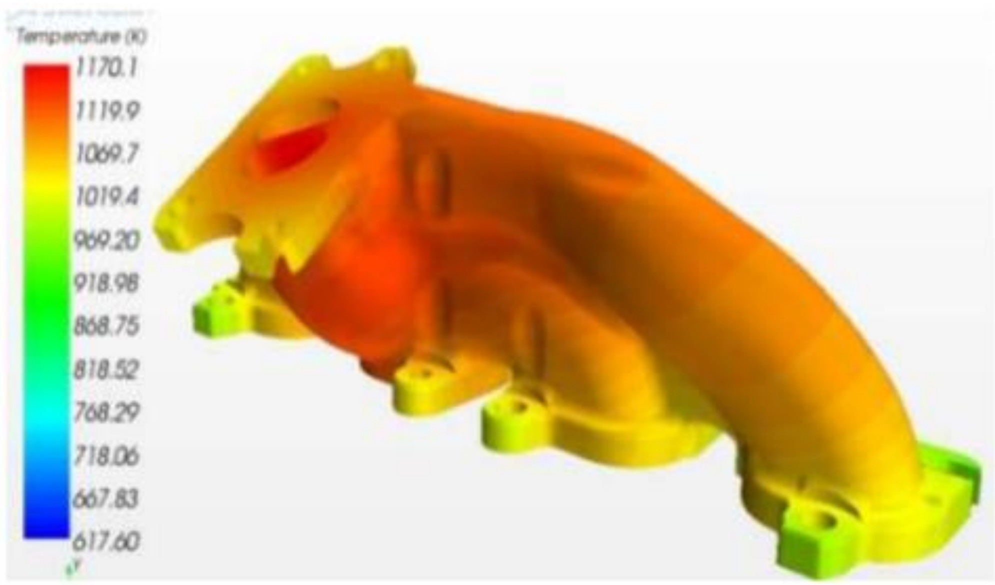

Figure 2.1. Steady temperature calculation result. (Liu et al., 2013)

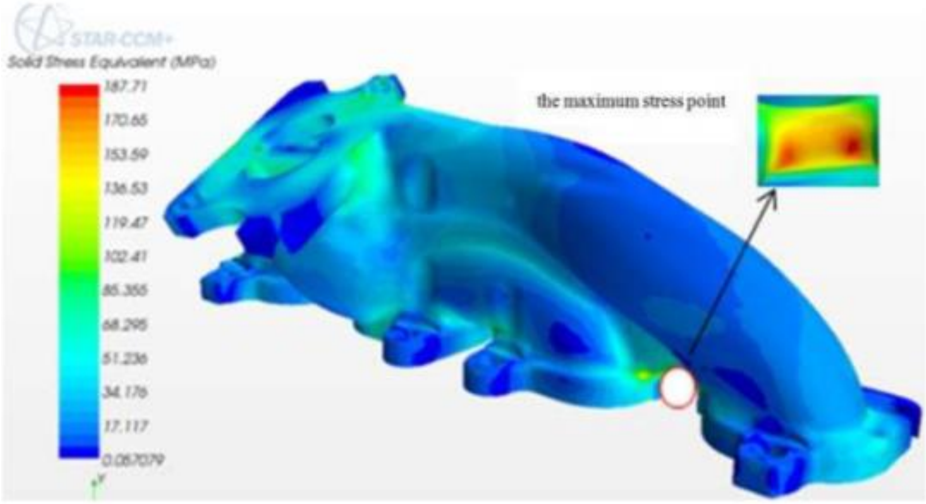

Figure 2.2. Steady thermal stress calculation result. (Liu et al., 2013)

M Kumara Varma and Suresh Kumar deal with the thermal and structural analysis of a multi cylinder engine exhaust manifold, for the given extent. Thermal and Coupled Field analysis are performed. Critical frequentness in the operating range is attained by performing Modal analysis. Harmonious analysis is performed and the deviations and stresses at the nearest natural frequentness are colluded. After the results attained from different analysis, exhaust manifold design's acceptance is done. Results show that flow action and velocity of the exhaust gases inside the pipe can be analyzed by conducting computational fluid dynamics which will help to optimize the design of exhaust manifold.(M Kumara Varma et al., 2014)

De Azevedo Cardoso and Andreatta focused on the Thermomechanical Fatigue (TMF) analysis for an exhaust manifold and this study showed the estimation of fatigue life of exhaust manifold under thermo-mechanical loads. Bolt pressure and temperature field has been applied in order to get variation on stresses, going from under normal circumstances to a full condition. Low cycle fatigue (LCF) has been considered to estimate the exhaust manifold under the stress cycles produced by temperature change. Thermal and stress analysis have been performed by ABAQUS. To conclude, the number of cycles estimated for the turbocharger has also been estimated. In both cases, the life estimation is above the minimal number of cycles needed. Generally, in experimental tests the failure occurs between 1000 and 10 000 cycles and as bolt tensioning and contact regions are represented in the model, the factual slippage between the manifold and the cylinder head can be well estimated. Gasket opening and gas leakage also can be approached with the modelling herein employed.(De Azevedo Cardoso et al., 2016)

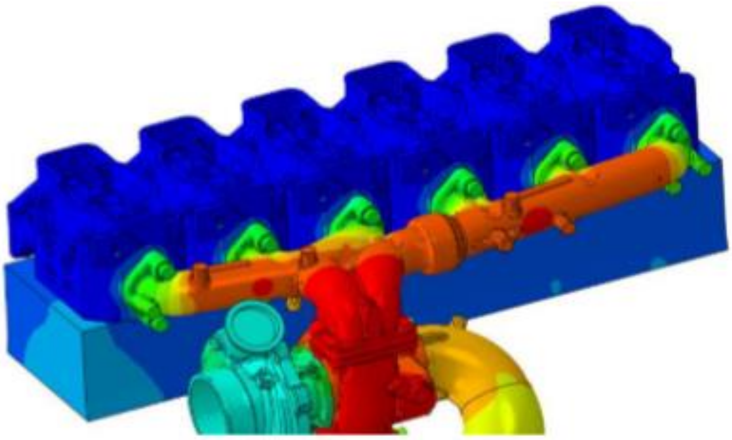

Figure 2.3. Temperature distribution for full load condition. (De Azevedo Cardoso et al., 2016)

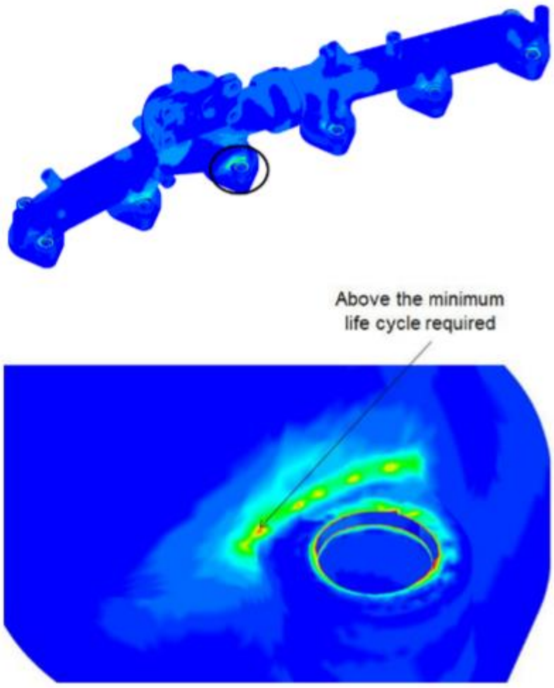

Figure 2.4. Number of cycles for exhaust manifold failure. (De Azevedo Cardoso et al., 2016)

Gopal and Rao investigated to find out pressures and velocities at varied mass flow rates in the exhaust manifolds with Long Bend Side Exit (LBSE), Long Bend Middle Exit (LBME) and Reducer. This disquisition also to figure out the performance of the exhaust manifold with varied modifications in its design or adding an element for the exhaust manifold to increase its effectiveness. In the current analysis mass flow rates considered in the exhaust manifold are 2 kg/ s, 4 kg/ s, 6 kg/ s, 8 kg/ s, 10 kg/ s, 12 kg/ s in all the varied modifications

in the exhaust manifolds. From the that examinations it’s set up that Long Bend Middle Exit (LBME) with Reducer is giving the better performance.(Gopal et al., 2017)
Ultramodern diesel engines are complex assemblies with tight packaging constraints, and due to advanced temperatures because of turbocharging, they've largely non-uniform temperature distributions, which are challenging to prognosticate. Ford Otosan automotive manufacturer uses Simcenter STAR- CCM to fleetly produce better diesel engine designs and Simcenter STAR- CCM provides the occasion to directly assess the performance of several engine subsystems and determine the loads and shape of the factors and systems. The increased simulation accuracy has led to the rise of multi component, multiphysics computational fluid dynamics (CFD) simulation as a fundamental demand. To this end, Ford Otosan used co-simulation on two critical engine factors, the engine exhaust manifold, and the piston head, to see how it could help them achieve their design goals. Ford Otosan used three analysis system to compare which system is most accurate. These are sequential coupling method, co-simulation method, the conjugate heat transfer method. Analysis show that using Simcenter STAR- CCM+ co-simulation enables coupling of multiphysics simulations with different time scales ranging from microseconds to thousands of seconds, furnishing briskly and more accurate analyses and shorter development times for development and assessment of complex designs.(Siemens, 2018)
Cihan and Bulut had studied a numerical study has been conducted to determine how fluid materials and manifold types of behave in two different types of common automotive manifold designs. The following conclusions show that due to characteristics of gasoline energy, gasoline energy had significantly lower pressure and velocity as compared to both other energies studied. CFD was used to try out two different multifarious designs, with three different points (1, 2 and 3) being considered for analyses of pressure, temperature, and velocity changes. A CFD procedure was used to analyze the changes in temperature, pressure, and velocity in two different multifarious designs.(Cihan et al., 2019)
Patil and Bhat investigated the heat transfer analysis for manifold of different material such as aluminum alloy, cast iron and mapping of this thermal load is done for structural analysis to check stresses and distortions under safe limit and deals with carrying out steady state heat transfer analysis for two material and coupled analysis of thermo-mechanical is done to check maximum diversions of manifold and different stresses on the manifold and bolt. Meshing is done by Hypermesh software and analysis is done by using Abaqus software. In the operation where the multifarious outside temperature will be over to 300°C the aluminum manifold

material can be used in place of cast iron material with more factor of safety. Magnitude of distortion induced in the manifold for both the materials are veritably small. Working stresses induced up to 300°C temperature in the aluminum alloy is lower than the cast iron material due to low stiffness. High strength to weight portion can be achieved i.e. For the same volume of aluminum material manifold element weight will be 2.75 times lower weight than the manifold made of cast iron material. Through of good thermal conductivity characteristic of aluminum material better heat distribution can be achieved. Well castability and complex shapes can be casted through of good inflow of material in the mould due to its low viscosity.(Patil et al., 2020)

Table 2.1. Induced stresses under Thermo-Mechanical loading for aluminium alloy and cast iron manifold. (Patil et al., 2020)

Material	**Working Stress (in Mpa)**				**Yield Strength at 300 °C**	**F.O.S**
	Von - Mises	**Tres-ca**	**Max-Prin**	**Min-Prin**		
Aluminum Alloy	18.36	21.15	16.11	2.65	160	7.56
Cast Iron	50.38	57.95	35.81	8.38	380	6.55

Nichal and Umale investigated how different parameters of the manifold, such as material type and geometric sizes, have an influence on the efficiency and performance of an automobile engine, and how they impress the efficiency and performance of the engine. Also clarifies how back pressure are often reduced by certain change within the geometry of the manifold. At different points throughout the manifold, changes in pressure, velocity, and temperature were mathematically computed. Performed the CFD analysis of exhaust manifold using Ansys Workbench. Finally, study shows that using of smooth corners and fillets lowers help to reduce the returning pressure to the engine.(Nichal et al., 2021)

In this research, Erken compared the analyzes made with computer aided programs by performing TMF life tests with the test rig installed in the center of the Ford Otosan Kocaeli Factory of the heavy commercial diesel engine exhaust manifold. The main objective in this study is to develop a method for thermo-mechanical fatigue life calculation, to design a thermo-mechanical fatigue test rig that reflects the real operating conditions for a diesel engine exhaust manifold, to make sure that the designed system is in a much better condition than the test sample in terms of life. design verification with static and fatigue analysis and to develop an analysis method for the exhaust manifold that is consistent with test results. The static and vibration characteristics of the designed system were calculated with the Hypermesh finite element program. STAR CCM+ was used as CFD analysis software to determine the temperature distribution created by the hot gas passing through the exhaust manifold. The resulting temperature distributions were determined by using the finite element software ABAQUS to determine the shape changes and stress values in the exhaust manifold geometry. As a result, the calculated fatigue lives were compared with the test results, and it was found that the numerical results were correct with a margin of error of approximately 15%.(Erken, 2015)

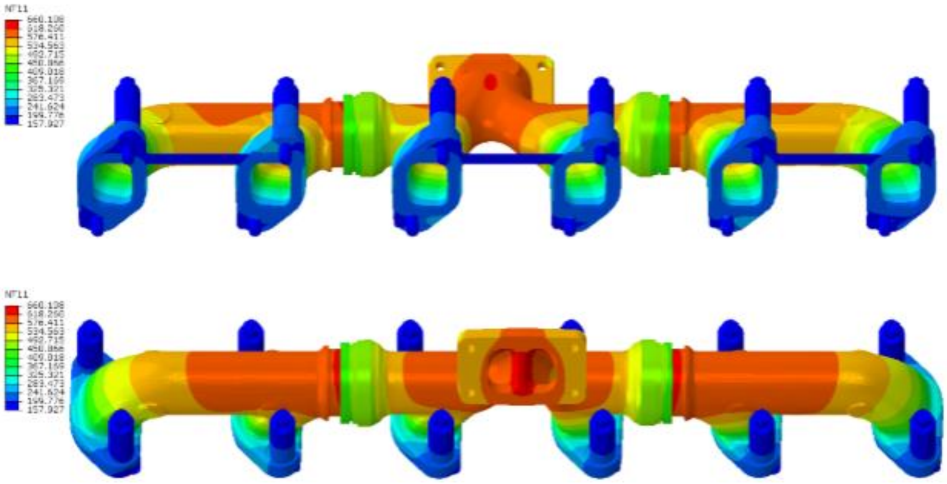

Figure 2.5. Exhaust manifold temperature distribution at end of the heating step. (Erken, 2015)

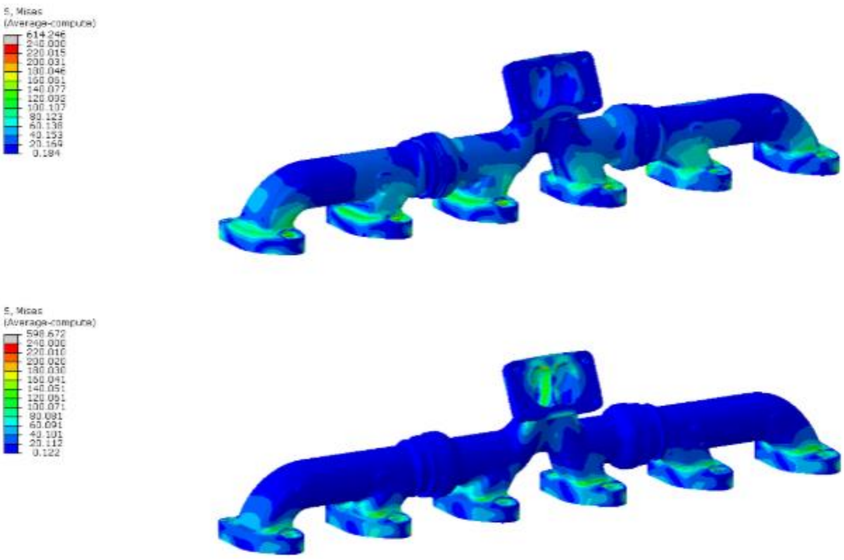

Figure 2.6. Von-Mises stress distributions for heating up and cooling down steps. (Erken, 2015)

Duman investigated the feasibility of three different CAE approaches called Conjugate Heat Transfer Analysis, Sequential Coupling, and Co-Simulation to use for the simulation of exhaust manifold fluid flow and the accompanying thermal distribution. The predicted metal temperature is then used to realize the thermo-structure durability analyses to evaluate the design of HD diesel engine exhaust manifold which is not beyond the scope of this study. Star-CCM+ Co-Simulation method leaps out with run time saving and getting more reasonable metal temperature distribution compared with experiment output.(Duman, 2016)

Yalçındağ experimentally and numerically investigated the exhaust manifold metal temperature for the stabilized maximum power operating point (1800 rpm) of a 13-liter diesel engine of a heavy commercial vehicle. Experimental studies, nominal test data (temperature, pressure, etc.) were collected for different steady state operating conditions of the diesel engine. Then 3D computational fluid mechanics analyzes were made by finite volume method. At the end outdoor heat convection coefficient optimization study was performed by using SHERPA algorithm with Optimate+ software. The results show that, temperature distribution of the exhaust manifold has been calculated correctly with an acceptable error. In this way, it is possible to make endurance calculations safely. Thus, structural weaknesses are prevented at early design stages and optimum product is obtained with minimum cost. (Duman, 2016)

Table 2.2. CAE Thermal Modelling Approaches Comparison Table (Duman, 2016)

Criteria	**Sequential Coupling**	**Star CCM+ Co-Simulation**	**Conjugate Heat Transfer**
Run Time	+	++	+++
Pre-Processing	++	++	+
Accuracy	+	++	+++

3. MATERIALS AND METHODS

3.1. Exhaust Manifold Design

Design of exhaust manifold plays important role to prevent fatigue and thermal failures.

The main function of the exhaust manifold is to collect the exhaust gas in one area and guide it to the next system as an adapter. Due to their position and function within the engine, the exhaust manifold consists of a combination of intake and exhaust ports. That is, it is formed by combining several gas inlets and one gas outlet.

Figure 3.1. Exhaust Manifold Examples of Cast and Stainless Steel (Yalçındağ, 2018)

The exhaust manifold design can be divided into sections.

The first of these is the design of the wet surface. The wet surface is called the line where the flow of exhaust gas takes place. As a result of the air-fuel mixture taken by the engine, it produces exhaust gas and the amount of this gas varies according to the amount of air-fuel mixture taken into the cylinders. Wet road design also varies with the amount of exhaust gas produced. Wet track design is indirectly dependent on the amount of air-fuel mixture taken into the engine. The cross-sectional area of the wet surface must be large enough to direct the exhaust gas to the next system and the flow of the gas must be of good quality. The exhaust gas flow should be as uniform as possible so that there is no pressure loss.

In the next step, the outer surface is designed by providing the necessary wall thickness for the wet surface.

In the last step, details such as the design of the interfaces of the exhaust manifold with other components, the mounting requirements for the fasteners.

Compared to the past, today's engines have lower emission values with the developing technology. The methods of reducing the emission values of the engines vary. Within the framework of emission rules, 4-cylinder is widely used in passenger cars.
For these reasons, the exhaust manifold design, which is the subject of the thesis, was made according to the 4-cylinder internal combustion engine.
The exhaust manifold is designed for the 4.6L V8 configuration engine and you can find the engine's specifications below.

Table 3.1. Engine specification of exhaust manifold model

Powertrain Architecture	Internal Combustion Engine
Engine Displacement (L)	4.6
Engine Configuration	V-engine
Number of the Cylinder	8
Fuel Type	Gasoline
Compression Ratio	9.0:1
Bore and Stroke	90.2 mm X 90 mm

The exhaust manifold was designed using the CATIA V5 3D design program, guided by the listed design steps. Throughout the entire design process, the exhaust manifold has been designed considering that it is a part that is exposed to high temperature, static loads, vibration and working in contact with high soot gas. During the design, every detail on the piece was completed considering these conditions.

During the design, the following steps were followed in order.

- Identification of factors affecting exhaust manifold design
- The design of the wet surface of the exhaust manifold
- Giving wall thickness to the wet surface and forming the outer shell
- Designing the cylinder head flange
- Designing the turbocharger flange

3.1.1. Identification of Factors Affecting Exhaust Manifold Design

There are several factors to consider when determining what will affect your exhaust manifold design. These are basic elements such as the size of the part, the amount of thermal stress the part will experience, manufacturability and cost.

Additionally exhaust manifold must reflect individual material properties and loading conditions by providing adequate stiffness and low operating temperatures, and must also meet the key engine development factors of emissions, performance, and fuel economy.

Lightweight design principles in order to reduce CO_2 emissions and fuel consumption with less friction losses is realized by downsizing concepts, where small and compact engines are built. By evaluating these elements, the first lines of the design were determined.

3.1.2. The Design of Wet Surface of the Exhaust Manifold

Exhaust manifold design started with the design of the gas line, that is, the wet surface, where the exhaust manifold fulfills its basic function. The wet surface is the most important part to transmit the exhaust gas to the turbo system. The gas line is the path through which the exhaust gas will pass, and the surface surrounding this path is called the wet surface. Wet surface design can be defined as the first step of the exhaust manifold.

Important parameters such as the cross-sectional area of the wet surface and the ability of this cross-sectional area to accommodate the exhaust flow at desired pressures and speeds should be considered. It differs from the outlet section of the exhaust port of the cylinder head and the intake section of the turbocharger system. Therefore, attention should be paid to cross-sectional changes in geometry.

Finally, attention should be paid to the compatibility of the sections where the exhaust manifold will be connected and the parts connected to the exhaust manifold will be connected. The wet surface is designed by avoiding sharp surfaces and routing cylinder lines connected in a single main flow direction with appropriate rotation angles. The radiuses in these turns were made as large as possible and the exhaust gas flow was directed as linearly as possible. Each cylinder port is coupled with an exhaust manidold branch. The wet surface section should be slightly larger than the cylinder head exhaust port section. Likewise, the wet surface of the exhaust manifold turbo outlet section should be smaller than the turbo inlet section. This rule should be applied in the form of increasing the cross-sections in the gas flow direction at the part change.

The manifold branches are connected to the main line along the first section geometry taken from the cylinder head exhaust ports and the transition to the section geometry of the main line is made. The cross-section changes during the exhaust gas advance are as follows:

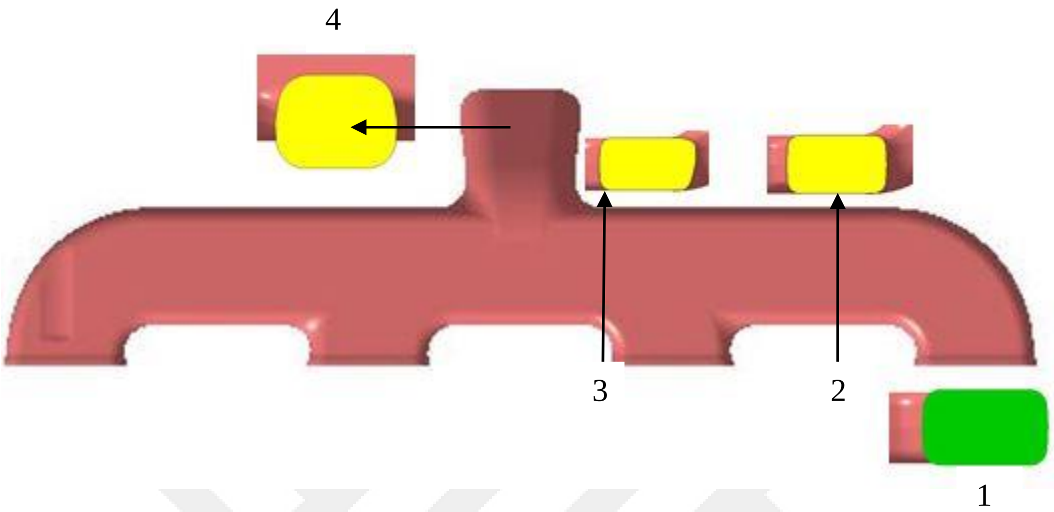

Figure 3.2. Exhaust manifold wet surface section change

The exhaust manifold has 4 cylinders as seen in the picture above, one turbo outlet (outlet 4). The cylinder head cross-section geometry is rectangular and merges with the main line by softening the corners and curving sideways. Due to the curved section geometry here, the exhaust gas flow will proceed linearly.

Section 4 shows the cross-section geometry of the turbocharger outlet. The cross-sectional area here is capable of passing all the gases coming from each line of the exhaust manifold. The cross-sectional shape of the turbocharger outlet is the section determined by the throttle section of the turbocharger valve.

Maximum attention has been paid to pressure losses and homogeneous flow in the wet surface design, turbocharger system outlets and cross-section changes, and has been designed accordingly. The wet surface, which is designed by taking into account the points to be considered, is shown in the image below.

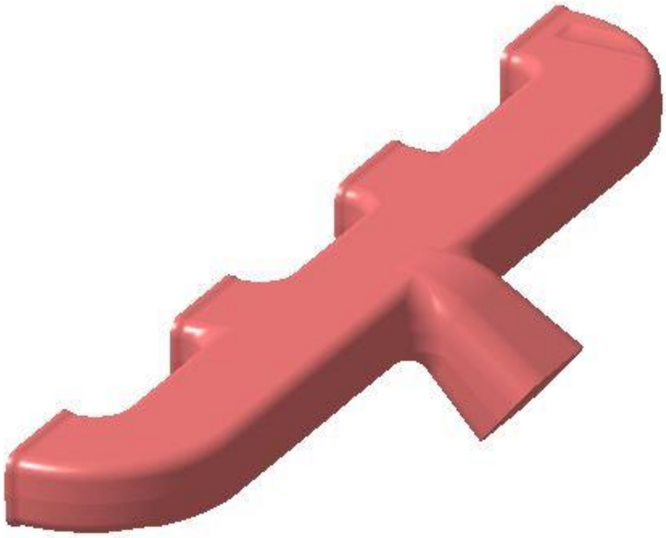

Figure 3.3. Exhaust manifold wet surface

3.1.3. Design of the Exterior Surface

The next step after the wet surface design is the outer surface design. To put it simply, the outer surface is obtained by giving the wall thickness from the wet surface to the outside. After the wall thickness was given, detailed operations such as increasing the radius in the low radius areas, minimizing the wall thickness imbalances, increasing the material thickness in the areas considered critical for strength, eliminating the reverse angles that could be an obstacle for the casting process and adding the mold angles were performed.

After these stages, the outer shell of the design is formed.

Figure 3.4. Exhaust manifold wall thickness

3.1.4. Design of Cylinder Head and Turbocharger Flanges

The final stage is in the design of the flanges. First, the flange of the exhaust manifold at the transition to the cylinder head connection was designed. Flange thickness values were determined by considering the weights of other engine components to be connected from the exhaust manifold. In passenger car engines, this value varies between 12 mm and 24 mm. The number of fasteners is two per connecting flange. The projections required on the flanges to secure these two fasteners have been added to the cast exhaust manifold model.

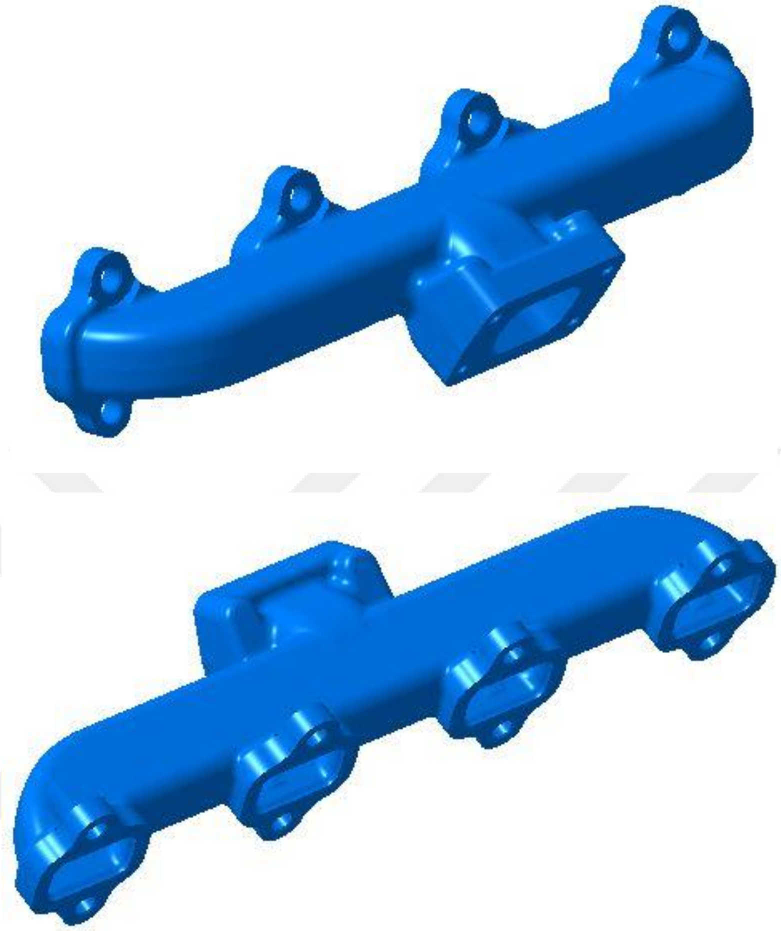

Figure 3.5. Exhaust manifold casting model

The most important element in the design of the flange of the turbocharger system is to meet the requirements that will be required depending on the desired assembly of a geometrically complex component such as the turbocharger system to the engine package with the appropriate flange design. Therefore, it is the position of the turbocharger system on the engine and the assembly process that determines the geometry of the turbocharger flange. The thickness of the flange is 12 mm, as in the cylinder port flanges. It was determined that 4 fasteners would be sufficient to ensure the connection of the turbocharger system with the exhaust manifold, and the flange location of the fasteners on the flange was determined so that the tightening tools to be used in the assembly line during the mass production process could reach it.

3.1.5. Connectors

The next step after designing the flanges and performing the tool checks is the selection and control of the fasteners and sealing elements to be used in the flanges. On the flanges of the cylinder head ports, 2 fasteners will be used at each port. These fasteners will be bolts. The 2 bolts to be used per port were chosen as M12x30 half threads. On the flanges of the turbocharger head ports 4 fasteners will be used. These fasteners will be bolts. The 4 bolts to be used per port were chosen as M8x35 half threads. The reason for choosing such long fasteners for a case where the flange thickness is 12 mm is to ensure that the part remains in the elastic region without plastic deformation during the elastic elongation of these fasteners, which will be exposed to high temperatures, and the elongation that will occur due to thermal expansions.

Static loads, vibration loads and thermal stresses are taken into account in the strength calculations of these bolts, and the strength classes of the bolts to be used are selected according to this calculation. However, due to the very high operating temperatures, a choice could not be made from the standard bolt classes. Instead, materials known as high-temperature bolting materials were chosen. According to this selection, the material of the cylinder head fasteners X22CrMoV12-1 in the DIN EN 10 269 standard has been determined as the material of the fasteners. The most important advantage of these materials is that the decrease in their strength with increasing temperature is less than that of standard materials.

Table 3.2. Fastener material and operating temperatures (DIN EN 10 269)

Material	Tensile Strength (MPa)	Max. Working Temp. (°C)
40 CrMoV 4-7	1040 - 1200	500
21 CrMoV 5-7	800 - 1000	540
X 22 CrMoV 12-1	800 - 1050	580
X6NiCrTiMoVB-15-2	900 - 1150	650
NiCr20TiAl	1000 - 1300	800

The change of this pressure force with increasing temperature is directly related to the fastener material. The thermal expansion of the fastener material should closely match the expansion of the exhaust manifold. The fasteners will also be exposed to high temperatures.

Especially bolt head will also as a heat barrier. Therefore, X 22 CrMoV 12-1 material, which is clearly robust than same standard material class, was chosen as the bolt material.

The compression force provided by the fasteners increases with increasing temperature. Undoubtedly, the reason for this increase is that the thermal expansion of the flange made of 18 mm SiMo material is higher than that of the connecting element. The last control that needs to be done here is to check the strength of the bolt under higher temperature conditions. This control was carried out at 705 ºC in order to be safe and the axial tensile stress to be applied to the bolt at this temperature was calculated as ~430 MPa. The yield strength of the fasteners at 705 ºC is ~472MPa. As a result of this comparison, it was concluded that the bolt remained in the safe zone even at the maximum exhaust gas temperature.

It was decided to use M10x40 bolts made of the same material in the flange of the turbocharger system. All of the calculations for the cylinder head flanges have been made for this connection as well, and safe results have been obtained, just as with the head bolts and head studs. Unlike cylinder head flange fittings, this flange does not require thermal expansion routing. Because, due to the dimensions of the turbocharger system outlet, thermal expansions in these regions do not pose a threat on the manifold.

3.2. Exhaust Manifold Material Definition

Although the exhaust manifold is not directly exposed to the heat released as a result of the combustion in the cylinders, it is exposed to high temperatures by the conduction and convection of heat through the waste gases.

Considering these criteria, it is essential that the material of the exhaust manifold can withstand temperatures of 700 and above.

In material selection, attention should be paid to its mechanical properties at variable temperatures, thermal expansion of the material, vibration, noise and acoustic performance, oxidation resistance and cost.

The materials used for the exhaust manifold may vary according to the production method. Below is a table for materials and operating temperatures.

Table 3.3. Exhaust manifold materials and maximum working temperature information. (Gocmez et al., 2009)

EQ No.	Material	Maximum Working Temperature (°C)
1	X5CrNi 18-10 (Stainless Steel)	800-850
2	X6CrNiTi 18-10 (Stainless Steel)	850-920
3	X2CrTiNb 18 (Stainless Steel)	900-950
4	X15 CrNiSi 20-12 (Stainless Steel)	950-1000
5	GJS-SiMo-5.0-1.0 (Cast Iron)	700-830
6	GJV-SiMo-4.5-0.6 (Cast Iron)	800-860
7	GJSA-XNiSiCr 35-5-2 (Cast Iron)	850-1050
8	GX40CrNiSi25-20 (Cast Iron)	1050-1100

The thermal deformation of the exhaust manifold, which is closely exposed to thermal loads, should be minimal. Otherwise, large plastic stresses and fatigue cracks will cause the exhaust manifold to fail. The choice of manifold material that can withstand maximum temperatures together plays an effective role in solving such problems.

The mechanical properties of stainless steel are more advantageous than cast iron, but the lower cost of cast iron makes it the primary reason for its use as an exhaust manifold material.

Considering the high thermal conductivity and low thermal expansion coefficient of the materials listed in the table 3.3, the material called GJS-SiMo-5.0-1.0 was chosen for the exhaust manifold.

HiSiMo, the most widely used material for exhaust manifolds, is an alloyed spheroidal graphite cast iron containing high Silicon(Si) and Molybdenum(Mo). With the increase of Silicon (Si) and Molybdenum (Mo) in its content, the durability and thermal properties of the material improve at high temperatures.- (De Azevedo Cardoso et al., 2016)

Containing 4-6% silicon and more than 0.3% molybdenum, HiSiMo features excellent high-temperature strength and oxidation resistance.

Table 3.4. Composition of the HiSiMo (Erken, 2015)

C	Si	Mn	P	S	Mo	Mg	Fe
3.26	4.28	0.21	0.018	0.010	0.48	0.032	Bal

Table 3.5. Exhaust manifold material(GJS-SiMo-5.0-1.0) physical characteristics.(Erken, 2015)

Temperature (°C)	Elastic Modulus (GPa)	% 2 Proof Stress (MPa)	Ultimate Tensile Strength (MPa)
20	168	412	632
100	165	371	585
200	162	357	557
300	159	342	536
400	154	326	486
500	146	266	358
600	139	175	192
700	118	80	98
800	86	32	38

The temperatures to which the exhaust manifold is exposed are 700-800 °C on average. The tensile properties of HiSiMo, which is the material that can function at these temperatures without deteriorating its mechanical and physical properties, are also available in the table above.

The table shows that this material has minimum value of both elongation and reduction in cross-sectional area is seen at 400°C.(Erken, 2015)

3.3. Analysis Infrastructure

Based on previous experiences and experimental data, the design and material selection stages are completed. However, even if everything goes well at these stages, computer-aided analyzes should be performed for the exhaust manifold exposed to high temperatures before encountering irreversible errors.

Metal temperature during heating and cooling cycles is very important in thermomechanical analysis. The analysis of heat transfer in an exhaust manifold is a typical problem between fluid and solid domains. Therefore, these CAE studies require a combination of CFD and FE solvers.

Briefly, TMF analysis can be divided into three main parts. The first part is a heat transfer analysis, and the second part is a transient nonlinear finite element analysis of the exhaust manifold. The final step is to determine the number of fatigue life cycles. (Erken, 2015)

The waste gas released as a result of the combustion in the cylinders is basically a fluid, and we should know that this fluid has energy due to its mass, velocity and temperature.

In a mechanical sense, the conservation of mass, momentum and energy of this fluid needs to be examined.

Firstly, to start with conservation of mass or the law of conservation of matter states that, the net mass transfer in and out of a given volume in the time interval Δt is equal to the net mass change remaining in the volume.

The law could be formulated mathematically of fluid mechanics.

$$\frac{\partial_\rho}{\partial_t} + \nabla . (\rho \mathrm{v}) = 0 \tag{3.1}$$

p is the density, *t* is the time, ∇ is the divergence, and **v** is the flow velocity field.

$$\frac{dM}{dT} = \frac{d}{dt}\int \rho dV = 0 \tag{3.2}$$

M is the total mass, d*V* is the derivative that defines the integral over the whole volume of the system.

The next one is momentum conservation. Newton's second law is commonly known as the linear momentum equation. This equation is the mass times the velocity of the object, and its direction is the same as the direction of velocity. A change in the momentum of a substance occurs when a net external force acts on the substance. The acceleration of an object is directly proportional to a force acting on it and inversely proportional to its mass.

Variation of momentum with time in the control volume:

$$\frac{\partial}{\partial t} \int_{\Omega} \rho \vec{v} \, \partial\Omega \tag{3.3}$$

The last one is that conservation of energy. The first law of thermodynamics must be understood before we can comprehend the idea of energy conservation. This rule states that any change in the total energy in a volume over time relies on the net work performed by the forces operating on the volume and the net energy flux entering or leaving the volume. This interpretation applies to finite control volumes.(Yalçındağ, 2018)
The conversion of energy from one form to another occurs constantly. It should be known that the fluid's internal energy and kinetic energy per unit mass are added to determine its total energy per unit mass.

$$E = e + \frac{|\vec{v}|^2}{2} = e + \frac{u^2 + v^2 + w^2}{2} \tag{3.4}$$

For thermodynamic system, the first law of thermodynamics is formulated like that:

$$\Delta Q = dU + \Delta W \tag{3.5}$$

ΔQ is the amount of energy that a heating process given to the system, ΔW is the amount of energy that the system loses, and dU is the change in internal energy of the system.

Entropy is a function of a system's state that reveals the limits of how much heat may be converted into work. The work that the system does for a straightforward compressible system may be stated down.

$$\Delta W = PdV \tag{3.6}$$

P is the pressure and dV is a negligible change in the system's volume.

$$\Delta Q = TdS \tag{3.7}$$

T is the temperature and dS is a negligible change in the system's entropy.

The first law may be expressed as follows if an open system has many walls and the mass transfer occurs via stiff walls independently of the heat and work transfers:

$$dU = \Delta Q - \Delta W + \sum_i hi\, dMi \quad (3.8)$$

Where i and h_i is the appropriate enthalpy per unit mass and dM_i is the additional mass of species.

3.3.1. Heat Transfer

The natural direction of heat transmission is from a hot object to a cold item. Heat transfer, to put it another way, is the movement of energy and entropy from one place to another. The first law of thermodynamics states that heat transmission causes a change in the internal energy of the systems concerned.

Convection, heat radiation, and conduction are the common names for the specific processes.

Conduction is the process of transferring heat by causing molecular motion inside a substance, without the material itself moving. To put it another way, conduction is the slow-moving transmission of energy and entropy between neighboring molecules. Energy will stream from a part toward the cooler end if one end is at a higher temperature, because the faster particles will collide with the slower ones, transferring energy to the slower ones in the process.

Using Fourier's Law, conduction heat transfers may be measured. A material's thermal conductivity provides information on how well it transmits heat. The thermal conductivities of different materials vary greatly, with metals having the highest thermal conductivity, liquids having even lower thermal conductivities, and gases having the lowest thermal conductivities. The conduction heat transfer is:

$$\frac{Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x} \quad (3.9)$$

Where Q is the heat transfer, k is the heat transfer coefficient, t is time interval during which the amount of heat, A is the cross-sectional area, T is the temperature difference, Δx is the distance between the ends. The rate at which heat energy diffuses is indicated by the thermal conductivity coefficient. It varies depending on whether the stuff is solid, liquid, or gaseous.

Knowing the heat conduction coefficient (k) is important to apply Fourier's Law to heat transfer calculations. The rate at which heat energy diffuses is indicated by the thermal conductivity coefficient.

Convection is the process of transferring heat by the mass motion of a fluid, such as air or water, away from the heat source while carrying energy along with it. The expansion, decrease in density, and ascent of hot air over a heated surface is known as convection. Newton's Law of Cooling, which incorporates the heat transfer coefficient, is used to calculate convection. The heat transfer coefficient, like thermal conductivity, depends on the fluid's thermophysical parameters. It also depends on the system's physical qualities, such as the fluid's velocity and the shape of the flow field. The convection heat transfer rate is:

$$\dot{Q} = h\mathrm{A}\Delta\mathrm{T} \quad (3.10)$$

Radiation is the term used to describe the transfer of energy as electromagnetic radiation from its emission at a heated surface to its absorption on another surface. No matter what their temperature, all materials radiate radiation in all directions. Unlike conduction and convection, which both require a conducting medium, energy is transferred through radiation without the need for one of them. In other words, radiation heat transmission is possible in the absence of air. The transport of energy from the Sun to the Earth is made possible by this special characteristic. Similar to how light is understood by wave theory, radiation heat transfer is measured by the Stefan-Boltzmann Law. By interacting with surfaces that are at various temperatures, radiation can be absorbed, reflected, or transmitted. The emissivity, absorptivity, transmissivity, and reflectivity of a material are functions of its surface qualities that define its efficacy at emission, absorption, transmission, and reflection. The difference between the radiation released and the radiation absorbed by the surface is the net energy transferred by radiation. The radiation heat transfer rate is:

$$dQ = \varepsilon\sigma F(T_a^4 - T_a^4) \quad (3.11)$$

Where dQ is the heat flux, ε is the emissivity, σ is Stefan-Boltzman constant, F is the view factor, Ta and Tb are the absolute temperature of two parts.

3.3.1.1. Thermal Boundary Layer

The temperature difference produced by the thermal energy transfer between the surrounding layers defines the region of fluid flow referred to as the thermal boundary layer. Studying thermal and momentum diffusivity makes it simpler to comprehend how fluid frictional resistance and heat transport are related. The thermal boundary occurs when the sheet temperature differs from the flow temperature.

Fluid particles assume zero velocity when they come into touch with the surface. These particles then slow down the mobility of particles in the adjacent fluid layer, which slows down the motion of particles in the following layer, and so on, until the effect is minimal at a distance of $y = \delta_t$ from the surface. Shear stresses τ that act in planes parallel to the fluid velocity are linked to this fluid motion retardation and assume that $T_y = T_\infty$. However, fluid particles that come into contact with the plate attain thermal equilibrium at the surface temperature. (Bergman et al., 2011)

Thermal boundary layer development on an isothermal flat plate is shown in Figure 3.6

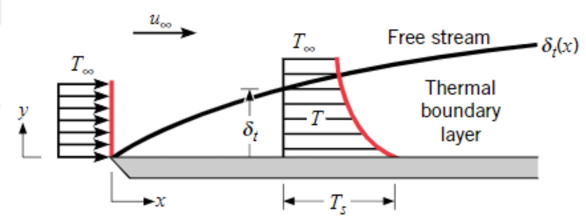

Figure 3.6. Velocity boundary layer development on a flat plate (Bergman et al., 2011)

Boundary layer thickness, or δ_t, is commonly defined as the amount of *y* for which the ratio $[(T_s - T)/(T_s - T_\infty)]$ = 0.99. The way that *u* fluctuates with *y* across the boundary layer is referred to as the boundary layer velocity profile.

It is simple to show the relationship between the circumstances in this boundary layer and the convection heat transfer coefficient.

Applying Fourier's law to the fluid at *y=0* will yield the local surface heat flux at any distance *x* from the main edge. This is,

$$q''_{surface} = -k_f \frac{\partial T}{\partial y}\Big|_{y=0} \tag{3.12}$$

Using Newton's law of cooling as a guide, we can observe that the subscript s has been used to stress that this is the surface heat flow and that:

$$q''_{surface} = h(T_{surface} - T_{\infty}) \quad (3.13)$$

Then, if these equations are combined and rearranged to obtain h:

$$h = \frac{-k_f \partial T/\partial y|_{\ y=0}}{T_{surface} - T_{\infty}} \quad (3.14)$$

The rate of heat transfer over the boundary layer is determined by the circumstances in the thermal boundary layer. Temperature gradients in the boundary layer must diminish as x grows because $T_{surface} - T_{\infty}$ is a constant that is independent of x and δ_t increases with increasing x. As a result, the magnitude of reduces $\partial T/\partial y$ as x increases, which implies that $q''_{surface}$ and h both decrease as x increases.

3.4. Analysis Methodology

After the exhaust manifold design is finished, it should be checked using analytical techniques to see if the design is strong enough to handle the forces it will encounter. The appropriate design adjustments should be done if a potential issue is found during the analytical controls.

The estimation of metal temperature during the heating and cooling cycles and the similarity of this estimation with real conditions are very important for thermal mechanical analysis. The CFD and FE solvers must be linked for these CAE investigations because exhaust manifold heat transfer analysis is a typical multi-physics issue with a significant interaction between the fluid and solid domains.(Erken, 2015)

It has been stated throughout the thesis that the exhaust manifold is exposed to high temperatures. The life cycle number of the manifold operating under extreme conditions, its resistance to high temperatures and the events that occur during the conduction of heat should be analyzed.

A test condition known as a TMF refers to a scenario in which cyclic, theoretically uniform temperature and strain fields are externally imposed, concurrently altered, and controlled along the gauge section of the part.For TMF analysis, respectively, heat transfer analysis, transient nonlinear finite element analysis (FEA) of the exhaust manifold and the number of fatigue life cycles will be determined.

The analysis stages of the exhaust manifold, the design of which has been completed and the material selected, are as in the diagram below.

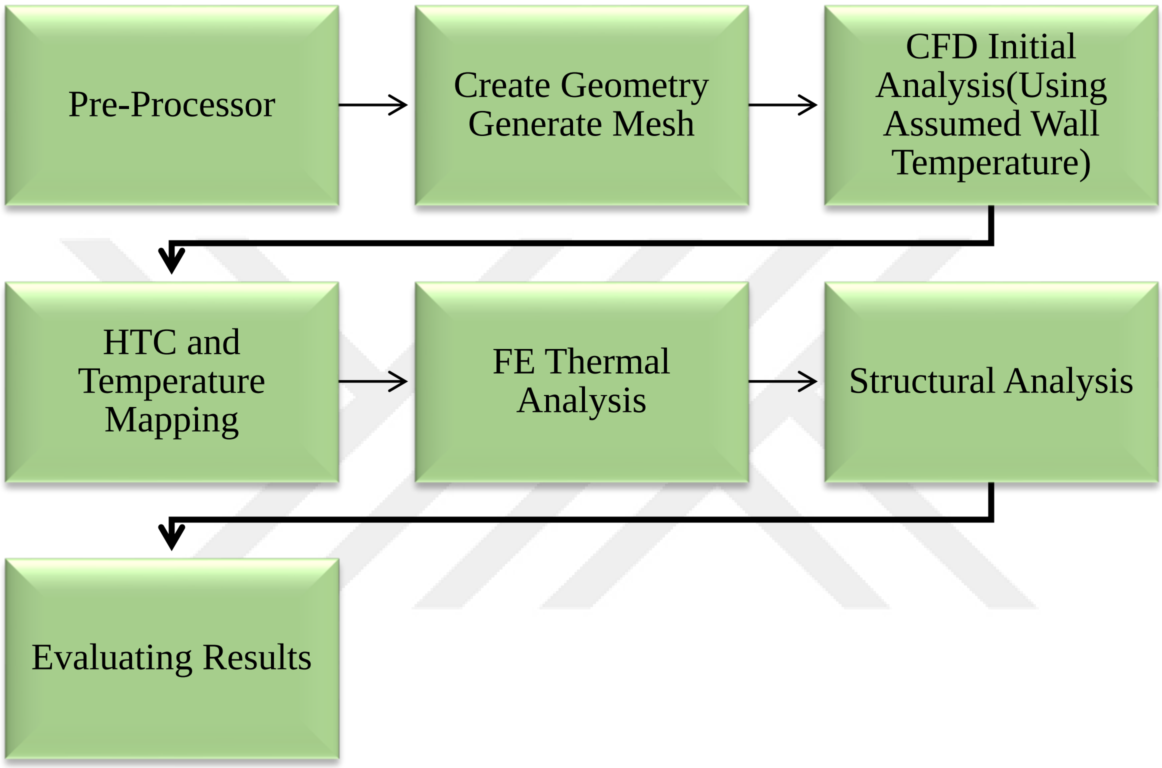

Figure 3.7. CFD and TMF analysis process sequence

3.4.1. CFD Analysis

The analysis of fluid flows using numerical solution techniques is known as computational fluid dynamics (CFD). Since CFD studies have a larger potential to accelerate the design process, they are more cheap and quicker than traditional testing for data collection. Additionally, in real-world testing, only a small number of values are assessed at once, but in a CFD study, all necessary quantities may be measured simultaneously and with a high level of spatial and temporal precision.

It should be emphasized that these CFD studies cannot completely eliminate physical testing processes because they only approximate a true physical solution. However, tests should still be run for verification purposes.

The following steps must be completed in the following order for the CFD analysis: create the model using key points, lines, areas, and volume commands; provide material properties; select the appropriate element; mesh the model to divide it into elements; apply the given loads; apply the boundary conditions; and finally, run the solution phase.
Various CFD analysis programs are used in the field of engineering. Abaqus, Ansys Fluent, Star-Ccm+ and Comsol are a few of them.

The consecutive explosion of internal combustion engines causes the admission of exhaust gases inward the manifold to occur cyclically. The sequence in which the cylinders are lit determines the order in which hot exhaust gases enter the exhaust manifold. The flow period change is time dependent. Extremely brief time intervals are required to resolve the flow field since the flow's behavior varies with crank angle during the duration of a duty cycle.

CFD analysis starts with the construction of the model and the specification of the material properties, then meshes the model to divide it into components. Finally, solutions are found by applying the specified loads and boundary conditions.

Before determining the boundary conditions, the properties of the material are defined. The material chosen for the manifold is cast iron and its specific properties are available in the table 3.5.
Table 3.6 contains the boundary conditions and material physical characteristics of solid exhaust manifold.

Table 3.6. Exhaust system boundary conditions of solid exhaust manifold.

Material	GJS-SiMo-5.0-1.0
Density	7 to 7.2
Maximum Working Temperature Tmax (°C)	700-830
Thermal Expansion Coefficient at 100°C (µm/mk)	11
Thermal Expansion Coefficient at 400°C (µm/mk)	12.5
Specific Heat Capacity at 100°C (J/gK)	0.475

In order to obtain a more accurate result in CFD analysis and TMF analysis, the materials in the surrounding parts of the manifold should be determined from the beginning. Representative parts for the engine block and turbo manifold were drawn during the design phase, and you can see the materials assigned for the bolt, engine block and turbo in the table below.

Table 3.7. Other material collections

Component	Material
Cylinder Head	EN-GJL-250
Turbo Charger	GJS-SIMO5.1
Exhaust Manifold Bolts	X 22 CrMoV 12-1

Table 3.8 contains the heat specifications of bolt steel. According to the table below, the thermal conductivity of bolt steel increases when temperature increases.

Table 3.8. Heat specifications of bolt steel

Temperature (°C)	Young's Modulus (MPa)	Thermal Conductivity (W/mK)
20	211000	12.7
100	206000	14.1
200	200000	16.0
300	192000	17.9
400	183000	19.8
500	173000	21.8
600	162000	23.9

Table 3.9 contains the heat specifications of EN-GJL-250. According to the table below, the thermal conductivity of EN-GJL-250 decreases when temperature increase.

Table 3.9. Heat specifications of EN-GJL-250

Temperature (°C)	Young's Modulus (MPa)	Thermal Conductivity (W/mK)
20	105000	51.1
100	102000	49.4
200	99000	47.2
300	96000	45.2
400	93000	43.4
500	90000	41.4

Table 3.10 contains the heat specifications of GJS-SiMo-5.0-1.0. According to the table below, the thermal conductivity of GJS-SiMo-5.0-1.0 first increases and then decreases with temperature.

Table 3.10. Heat specifications of GJS-SiMo-5.0-1.0

Temperature (°C)	Young's Modulus (MPa)	Thermal Conductivity (W/mK)
20	147000	20.2
100	145000	25.0
200	143000	26.5
300	138000	28.8
400	131000	29.6
500	118000	28.7
600	83000	27.9
700	47000	27.2
800	47000	27.0

Finally, to talk about the boundary conditions of the exhaust gas, the exhaust gas is composed of mixed unburned hydrocarbons, carbon dioxide, water, and other complex gases. Since it would be difficult to enter the amount of each gas as input into Ansys and to calculate its properties separately during the analysis phase, the exhaust gas was considered as a mixture of air and gasoline.

Table 3.11 contains the boundary conditions and physical characteristics of the fluids to be analyzed.

Table 3.11. Boundary conditions and physical characteristics of the fluids to be analyzed

Material	Air + Gasoline
Density	1.0685
Viscosity (Pa-s)	$3.0927\text{x}10^{-5}$
Specific Heat (J/g K)	1.056
Thermal Conductivity (W/mK)	0.0250
Heat Transfer Coefficient (W/m^2K)	50
Average Inlet Temperature (°C)	400 - 600
Output Gauge Pressure (Pa)	0
Inlet Velocity (m/s)	20
Inlet mass flow rate for 2 kg load at 1500 rpm (kg/s)	0.424
Inlet mass flow rate for 4 kg load at 1500 rpm (kg/s)	0.626
Outer Wall	Convection

As the fluid, air (gas+ gasoline) was employed. Throughout the investigation, the following parameters were held constant: molecular mass (kg/kmol), specific heat capacity $C_p(\frac{J}{kgK})$ and heat transfer coefficient $k(\frac{W}{mK})$. For the state equation, ideal gas is taken as a given. Additionally, the wall has a consistent heat flow and is non-slip in all directions.

In order to acquire the internal energy (J) and pressure P (Pascal) information of the flow, two state variables density ρ ($\frac{kg}{m^3}$) and temperature T (K) are used.

$$P = \rho RT \quad (4.1)$$

$$i = C_v T \quad (4.2)$$

3.4.2. Heat Transfer Analysis

For an exhaust manifold to be strong and lasting, it is crucial to be able to anticipate the metal temperature of the exhaust manifold properly. For unknown temperatures and flows under thermal loads, heat transfer analysis provides solutions. Heat transfer is a physical phenomenon that occurs when thermal energy moves from hot spots to cooler spots until thermal equilibrium is established.

Typically, a mixture of conduction, convection, and radiation processes are used to transport heat.

When the temperature differences causing the heat transfer are constant, or when thermal equilibrium has been reached, the temperature field does not vary any more. This type of heat transfer is known as steady-state heat transfer.

Transient heat transfer occurs over a short period of time, and when the thermal conditions change, the temperatures shift as well, eventually reaching a new equilibrium.

Given this reality, the first stage in the creation of a manifold is the precise prediction of the metal temperature of the manifold, which necessitates the coupling of CFD and FEA. The appropriate data type interchange on the interface between CFD and FE models is necessary for this iterative method between CFD and FE solvers.

3.4.3. TMF Analysis

The materials' mechanical behavior is significantly impacted by the engine's high temperature. Metal parts exposed to high temperatures over time experience sudden heating and cooling. Thermal mechanical fatigue (TMF), which is brought on by these temperature changes, is a type of wear. Typically referred to as short-lived fatigue, the TMF condition that develops in engines gradually reduces the lifespan of the parts it affects. When the car begins, the parts are exposed to these temperatures for as long as it runs, and when the car stops, they cool back down to room temperature.

The term "TMF" refers to a test scenario in which the part is subjected to cyclic, theoretically homogeneous temperature and strain fields that are externally imposed, concurrently changed, and regulated. Usually, these two variables are designed to move in a defined phase relationship and according to predetermined steps in time. The thermal strain component must always be accurately assessed for throughout a TMF cycle if a set mechanical strain range is necessary.

The vehicle's every start and stop are regarded as a cycle. Due to their resistance to thermal-mechanical fatigue and ability to satisfy demanding performance requirements, new generation special alloy materials have begun to be employed in regions exposed to high temperatures.

Perform transient nonlinear finite element analysis (FEA) is neccesary to simulate irreversible deformation and predict failure due to thermomechanical fatigue (TMF). Maximum temperature resistance and fatigue strength are two design considerations in multiple thermomechanical fatigue resistance.

It is possible to obtain the temperature distribution on the component using the temperatures of the gases impacting the wet surface that were determined from the fluid mechanics study.

However, in order to realize and analyze this, it will be necessary to match the high temperature wet surface and solid model.

The first transient CFD analysis is carried out on the assumption that the fluid exhaust gas domain's wall borders have uniform wall temperatures or uniform convection loads. After that, the fluid interface of the exhaust manifold construction is mapped using heat transfer coefficient and fluid temperature distribution.

How to use the flow field data from the CFD analyses stage as input data for FE thermal analysis is the key to coupling thermal analysis.

The main concern with coupling for thermal analysis is how to use the flow field data acquired from the CFD analyses stage as input data for FE thermal analysis. The CFD model is conducted for 3 engine cycles (2160 Crank Angle), each of which corresponds to 720 °CA and 2 crank revolutions.

Only the most recent engine cycle data, which is time averaged, is supplied as input for the FE study. The immediate findings produce misleading and incorrect solid temperature predictions, which is why time averaged HTC distribution is mapped onto FE thermal model. For the distribution of the Heat Transfer Coefficient (HTC), which is required for FE thermal analysis, the standard averaging approach is utilized over 720℃A.

$$\overline{HTC_\iota} = \frac{\sum_{i=1}^{720} \overline{HTC_\iota}}{720} \tag{4.3}$$

Weighted averaging method is employed for the gas side reference temperature distribution that will be submitted to the FE thermal analysis.
Instantenous time averaged:

$$\overline{T_\iota} = \frac{\sum_{i=1}^{720} HTC_i}{720x\overline{HTC_\iota}} \tag{4.4}$$

In order to more precisely compute the heat transfer that occurs in the solid model, bolts and a simplified cylinder head have also been included outside the exhaust manifold. It was defined that there was no contact resistance between the contacting surfaces. In this case, it was intended to provide the energy straight to the parts. This avoids a potential temperature decrease at the contact locations. This method was used to attempt to recreate the greatest temperature condition that the component could conceivably achieve. Also the materials of the engine head, turbo and connecting elements have been defined and the properties of the materials in the Table 3.7 will be used.
Thermal conductivity value of bolts, engine head, turbocharge and exhaust manifold behavior change with temperature. When temperature increases bolt’s thermal conductivity decreases, engine head’s thermal conductivity increases, manifold’s thermal conductivity increase and then decreases with temperature.

The entire solid model was defined at room temperature 27°C (300 K) for the starting condition. The beginning of the exhaust manifold thermal analysis phase is the first warm-up portion of the manifold. Initially, the outer surface of the manifold is at room temperature at 300 K. However, when the manifold completes the first warm-up phase, the temperature of the air in contact with the engine, manifold and surrounding components will reach 90 °C.

Under the hood creates a relatively closed environment. Therefore, the heat will leave the area more slowly from this partially closed environment compared to the open air conditions. Considering this situation, the outdoor temperature is assumed to be 90 °C in the following phases, including the first heating phase of the manifold. The temperature of the external environment data combined with mean temperature of the exhaust gas of the flow from the flow analysis provided the essential boundary conditions for the heat transfer study. The temperature of the air were maintained throughout the investigation since the air could not be modeled as the external fluid. Throughout the analysis, the material densities were taken constant.

3.4.3.1. Fatigue Life Analysis

Instead of simulating one load cycle as in a static analysis, a fatigue analysis is used to determine if a structure would fail after a specific number of repeated loading and unloading, or "load cycles." The component-wide fracture that started and spread across the component is what caused the fatigue failure.

The yield condition of the crucial components is assessed using the equivalent plastic strain (PEEQ) and this phrase denotes the outcome of a bulk strain measurement. Any area that is yielding will have a PEEQ value, and this value provides insight into how far along the material failure model that specific location is (starting point). A scalar representation of the plastic strain tensor is equivalent plastic strain (PEEQ). It is derived using the equivalent plastic strain rate integrated over time. It means the material has yielded if it is higher than zero. To get obtain a greater PEEQ, should be the higher yielding. Therefore, you just need to put the model into the plastic deformation area more in order to increase PEEQ.

Generally, for most materials, the PEEQ is defined as:

$$e^{peq} = \sqrt{\frac{2}{3}}\,||\in^{p}|| \qquad (3.15)$$

When interpreting fatigue life, PEEQ value is taken into account.

The other fatigue life prediction method is nCode design life program. It provides us with a thorough diagnostic fatigue procedure that allows us to estimate the operational lifespan of our product. Using the results of the finite element analysis, stresses and strains are calculated, then the life expectancy of the products is made by calculating the accumulation of damage under these cyclic loadings…

3.4.3.2. Transient Nonlinear Finite Element Analysis

The numerical method known as the Finite Element Method (FEM) which is called in Finite Element Analysis (FEA), which is a simulation of any physical process. With the help of this technique, components can be optimized at the design stage and minimize the amount of physical prototypes and trials that go into creating new products. To fully comprehend and quantify any physical event, such as structure or fluid behavior, thermal convection, mathematics must be used. Partial Differential Equations are used to describe the majority of these procedures. With the use of a computer, Finite Element Analysis method resolves these equations.

It's crucial to understand that FEA merely provides a rough solution to the issue and serves as a numerical approximation to determine the true outcome of these partial differential equations. By using a clearer technique, we are able to acquire the outcomes of phenomena like stress types, temperature change, and heat transfer that will occur at the spots in the material we have specified using the finite element analysis.

It takes a mesh of millions of small components coming together to form the shape of the structure in order to replicate it. There are calculations for each ingredient. The ultimate outcome of the structure is obtained by combining the separate findings.

The outcomes of phenomena like stress kinds, temperature change, and heat transfer that will happen at the spots we have determined in the material we have determined using the Finite Element Analysis are therefore obtained with a clearer approach.

4. ANALYSIS AND DISCUSSION

It starts with 3D fluid mechanics of analytical controls(CFD) for the exhaust manifold designed for the 4.6 L engine and continues with TMF analysis.

4.1. CFD Analysis Process

The 3D fluid mechanics study is the first step in the analytical controls for the exhaust manifold made for the 4.6 L engine.

In this study Ansys Fluid software was used for CFD analysis and the quality of the exhaust gas flow is controlled by utilizing the finite element method to analyze the flow rates, pressures, and gas temperatures. The designed manifold was imported to the Ansys for numerical analyses. Than the properties of manifold and materials around the manifold were entered into the Ansys software during the analysis phase.

A CFD analysis in transient mode was carried out since the internal features of internal exhaust gas flow of the manifold fluctuate dramatically and gradually during the course of cycle of an engine's operation.

For the manifold whose design has been completed, the material named GJS-SiMo-5.0-1.0, which is made of cast iron and specified in Table 3.5, was chosen as specified in the material definition section.

This material's thermal characteristics were specified, and it was admitted that these values varied with temperature. It was assumed that the specific heat capacity and heat transfer coefficient would fluctuate with temperature.

The heat transmission coefficient increases and subsequently drops with temperature, unlike the specific heat value, which changes linearly with temperature.

As the boundary conditions in the CFD domain, the pressure boundary condition type at the point of exit to the turbo boundaries and the mass flow intake boundary condition type at the path inlets were chosen, as illustrated in.

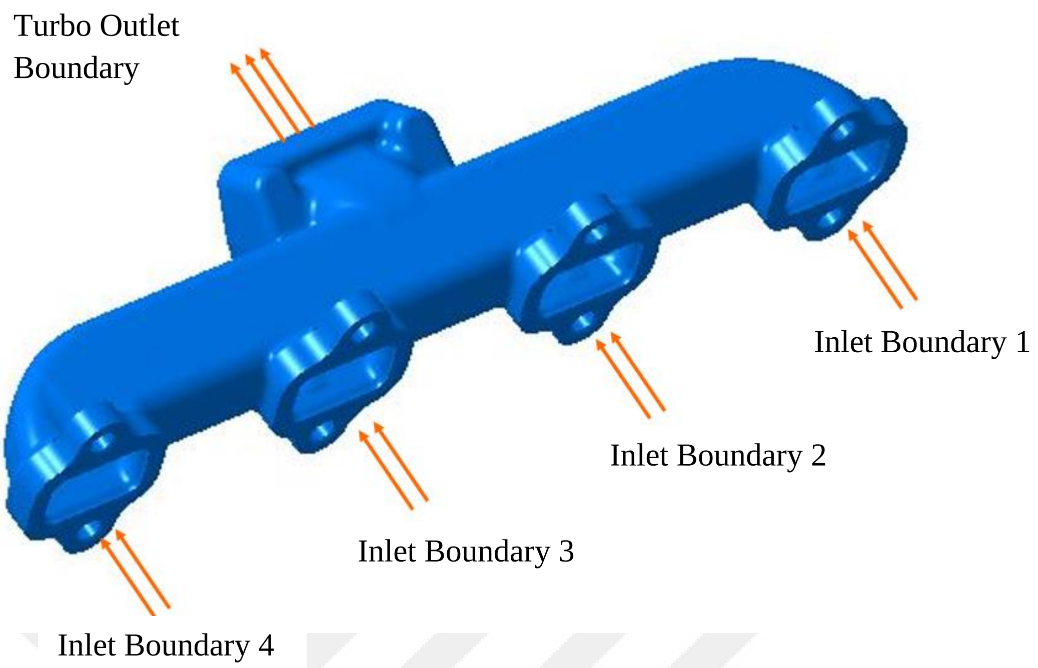

Figure 4.1. Exhaust manifold CFD domain

The significant density variations led to the assumption that the gas flow was compressible and due to the high velocities of the post-explosion exhaust gases, turbulence was chosen as the flow regime. In addition, steady state is used to be given as input to the thermal FEA analysis. Realizable κ-ε Reynold Navier Stokes (RANS) turbulence model was used for the solution.

Hexahedral cells are preferable for Computational Fluid Dynamics (CFD) applications because the generated mesh has less numerical diffusion. Unfortunately, creating such a mesh can take a lot of time, and if the geometry is complex, it might not be able to produce cells of high quality. Tetrahedral cells have been added to industrial pre-processors as a result. Their benefit is that even with extremely complicated geometry, they are simple to generate.(Sosnowski et al., 2018)
Eventually, tetrahedral mesh is used to improve the volumetric mesh and the quality of the mesh structure throw on an existing surface, as it gives faster and more accurate results. This method is frequently used in the literature.

460 000 tetrahedral solution mesh was created with the first layer thickness is 0.1 mm, 5 boundary layer 1.2 growth rate boundary layer parameters and element size 10 mm inputs. A

value of 0.9 skewness angle (measure of mesh quality) is provided.

In the images below mesh structure is shown , wet surface heat distribution in iddle conditions, wall heat transfer coefficient values in idle conditions, wet surface heat distribution in rated conditions and wall heat transfer coefficient values in rated conditions, respectively.

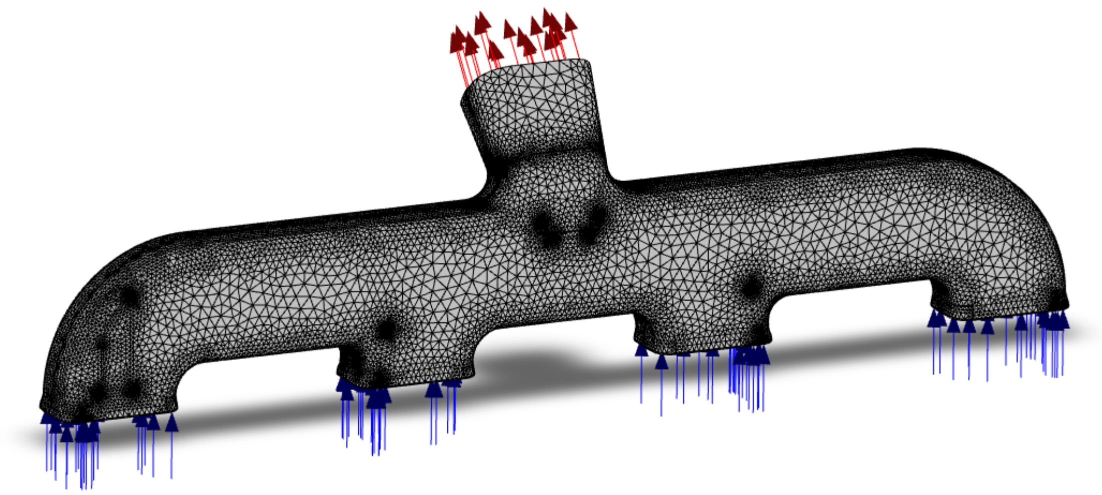

Figure 4.2. Exhaust manifold CFD mesh solution

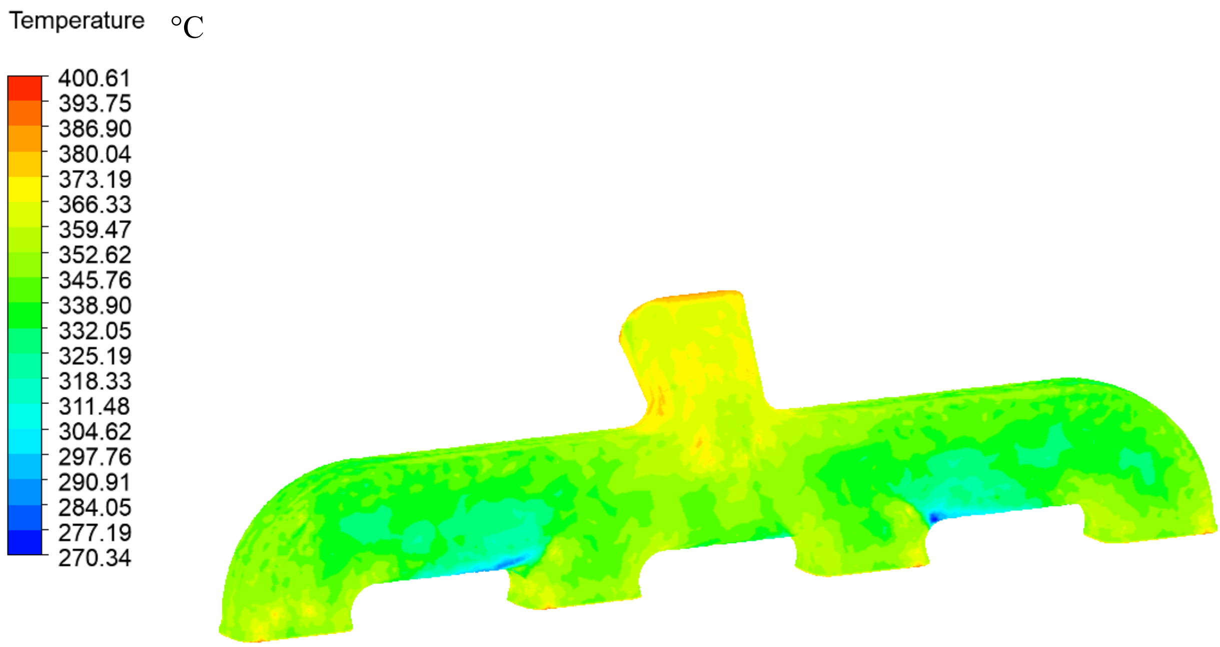

Figure 4.3. Exhaust manifold wet surface temperature distribution under idle condition

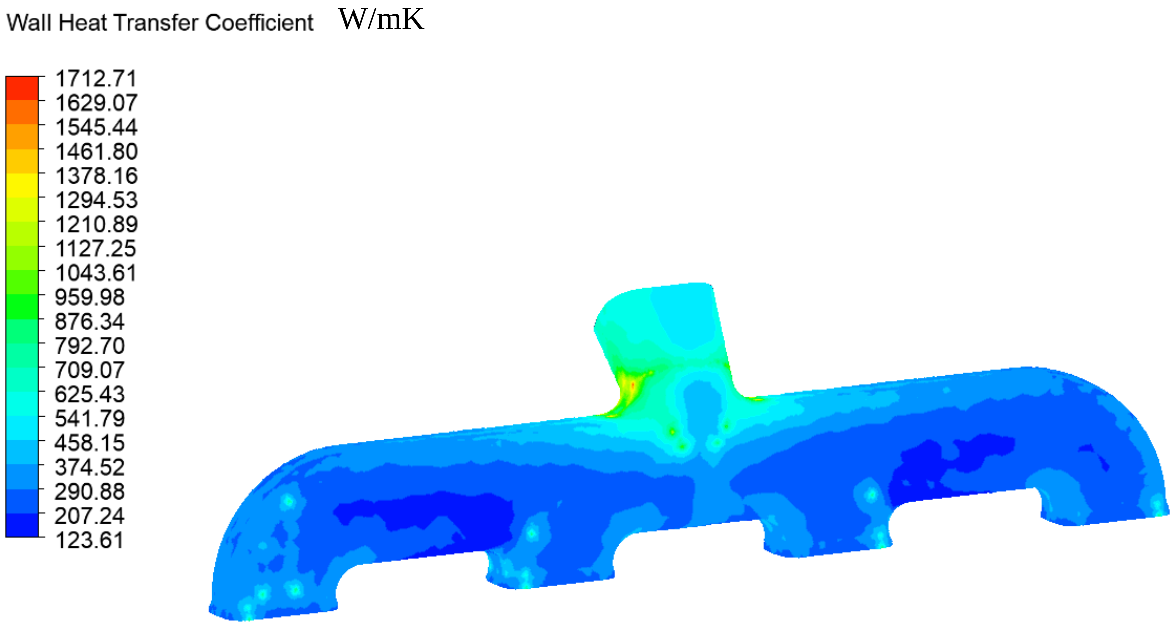

Figure 4.4. Exhaust manifold wall heat transfer coefficient under idle condition

CFD analysis shows that while the maximum wet surface temperature value is 400 C and the minimum temperature value is 270 C in idle condition. In addition Figures 4.4 shows that the HTC distribution changes slightly in the iddle condition.

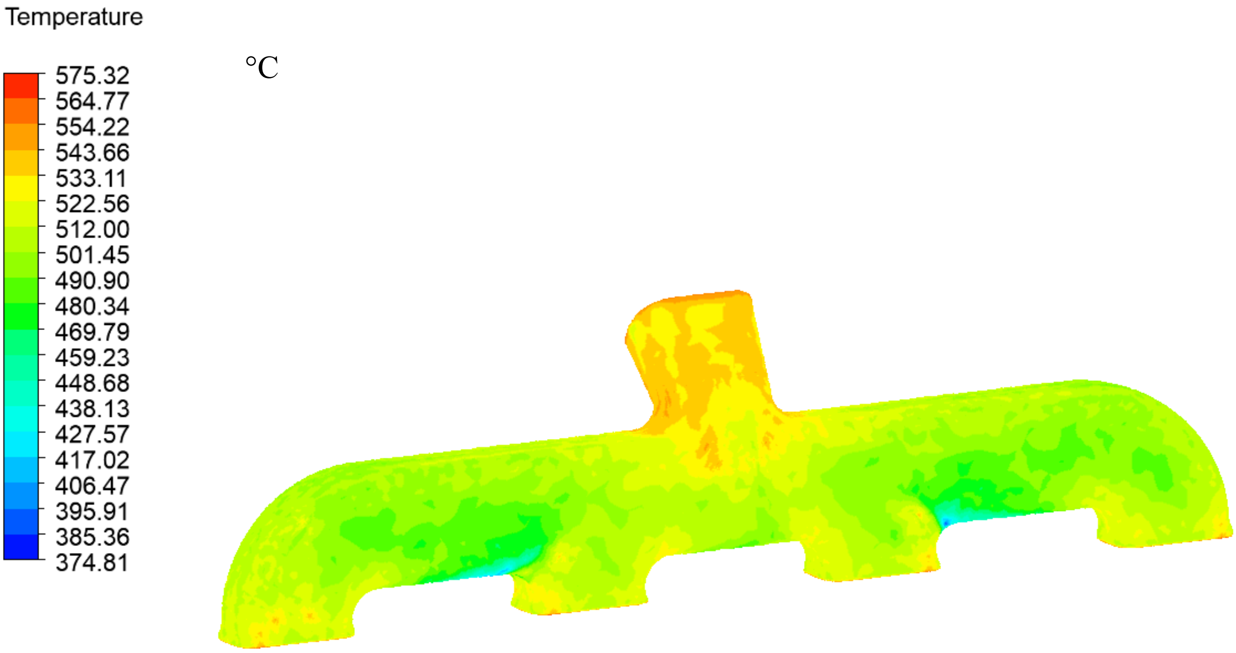

Figure 4.5. Exhaust manifold wet surface temperature distribution at rated condition

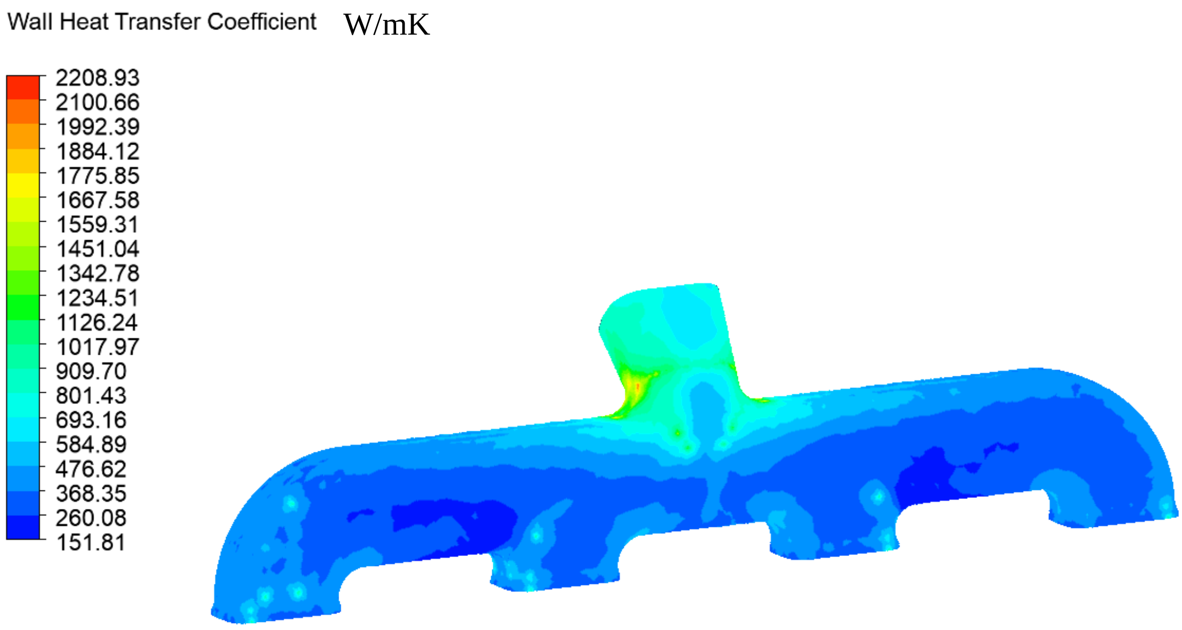

Figure 4.6. Exhaust manifold wall heat transfer coefficient at rated condition

The exhaust manifold's internal wall is exposed to exhaust gas with a temperature as high as 700 °C at peak power conditions. At the conclusion of the warm-up time, Figure 4.5 displays the temperature distribution of the internal wall of manifold structure as determined by thermal analysis. Temperature distribution at the turbo outlet of the manifold is slightly asymmetrical. The most thermally vulnerable portion of the manifold internal surface the turbo entry area (neck region), has the highest temperature values.

4.2. TMF Analysis

Heat transfer analysis and the temperature distribution it produces come next in the analytical process following the 3D fluid mechanics study. The exhaust manifold's material and the particular values of the material that will be needed throughout the study must be identified in order to move on with the analysis. These values are given in Table 3.6 where boundary conditions are defined.

Throughout the analysis, the exhaust manifold went through a series of warm-up and cool-down phases. The warm-up occurred initially assuming the engine was idling. In this phase, Idle steady state analysis was run. Then, to observe the response of the manifold to the heat when the engine is running at high speed, the flow rate values of the fluid in the manifold were changed and high speed simulation was made. Rated steady state analyzes have been run for these conditions. The heating and cooling analysis stages to which the manifold is subjected are as in the table below.

Table 4.1. Thermal analysis cycles

Load Description			**Duration (sec)**
Partial Cycle	heat-up phase (300 sec)	Acceleration	10
		Full Load	290
	cool-down phase (300 sec)	Deceleration	10
		Cool down	290
Full Cycle	heat-up phase (300 sec)	Acceleration	10
		Full Load	290
	cool-down phase (300 sec)	Deceleration	10
		Cool down	290

As seen in Figure 4.8, these heating and cooling conditions, the manifold was first exposed to high temperature for a while, assuming that the engine was running at high speed. Then, assuming the engine is idling, the hot manifold is allowed to cool down. This process was repeated two times in succession. The steps in Table 4.1 were applied to the manifold sequentially. The part was first exposed to high heat for 300 seconds, then a cooling phase took place for 300 seconds and this heating and cool down processes were repeated.

The temperature map for this manifold is seen in the images below. The hottest spot on the map is located in the center of the manifold, facing the on the wall of the turbocharger system extension and turbocharger entrance area(neck region). This temperature is in the range of 577 ºC.

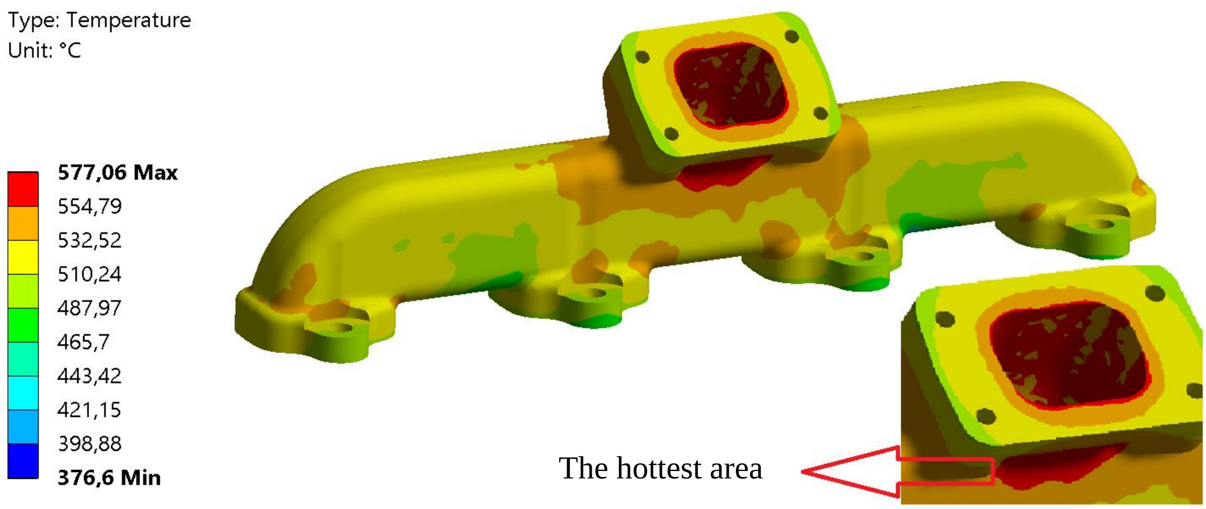

Figure 4.7. Exhaust manifold surface temperature distribution

Phases of thermal analysis are shown in Table 4.1. In the first stage, the manifold is exposed to heat for a while under full load conditions. At this stage, the walls of the manifold begin to heat up. The image of the initial phase is available below.

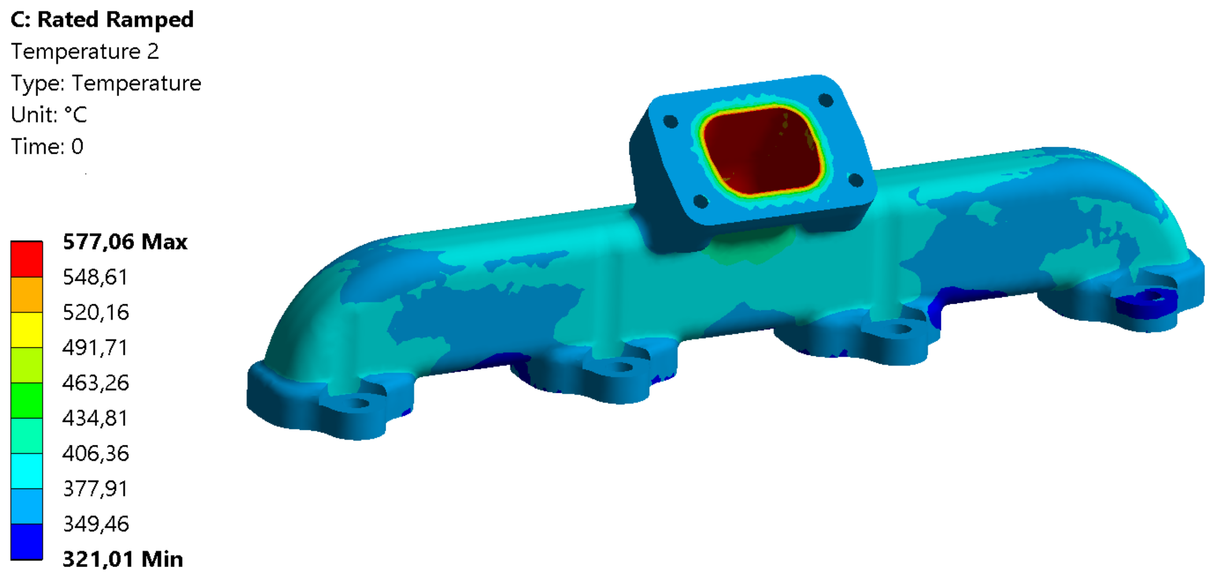

Figure 4.8. Exhaust manifold thermal analysis initial phase

Since the manifold, which is operated under full load conditions, is exposed to high temperatures, thermal accumulations gradually occur on its walls.

The state of the manifold, which has been exposed to full load (Steady State) conditions for a while, is available in the image below.

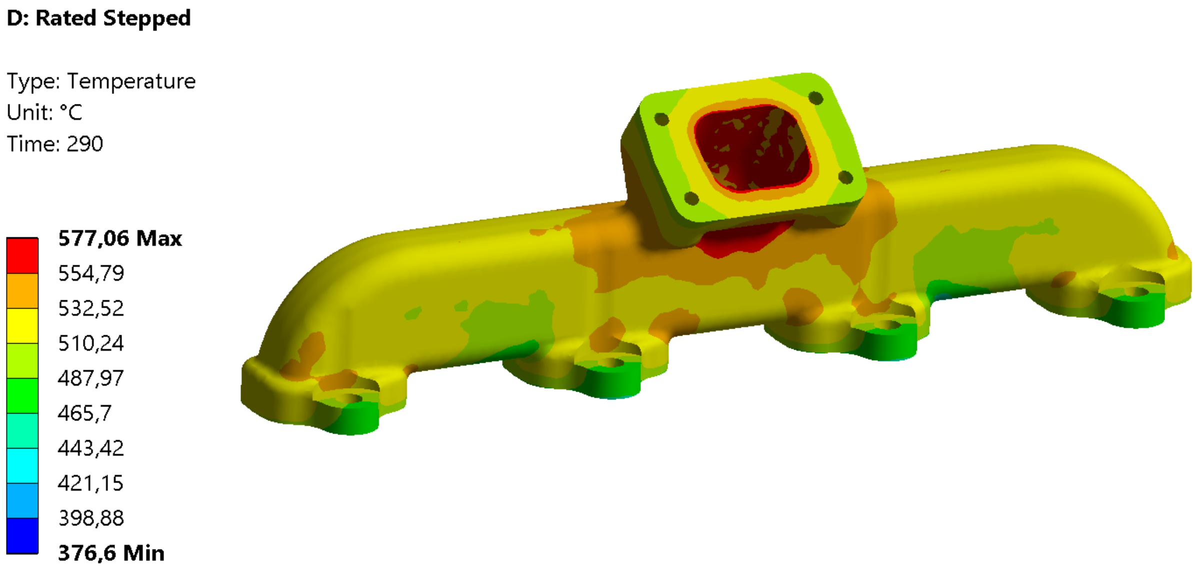

Figure 4.9. Exhaust manifold thermal analysis heat up phase for full load engine condition

As shown in Table 4.9, in the second stage, the cooling phase takes place while the manifold is in partial cycle. At this stage, the gas flowing through the manifold flows in iddle conditions. The image of the partial cycle cool down phase is available below.

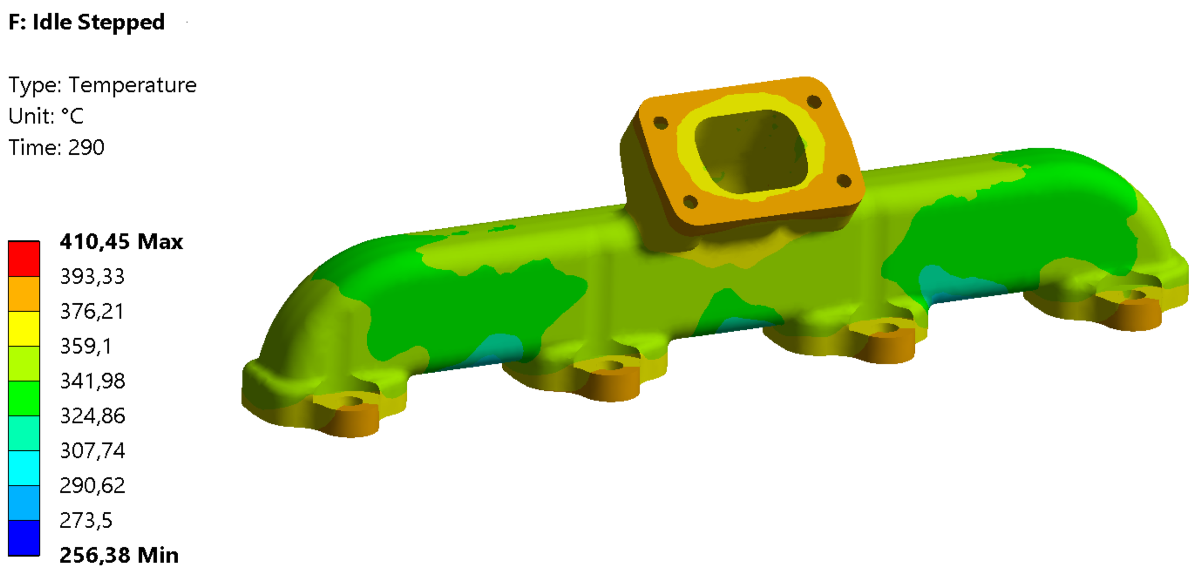

Figure 4.10. Exhaust manifold thermal analysis cool down phase

The state of the manifold, which has been exposed to heat when the engine operating full load (Steady State) conditions again for a while, is available in the image below.

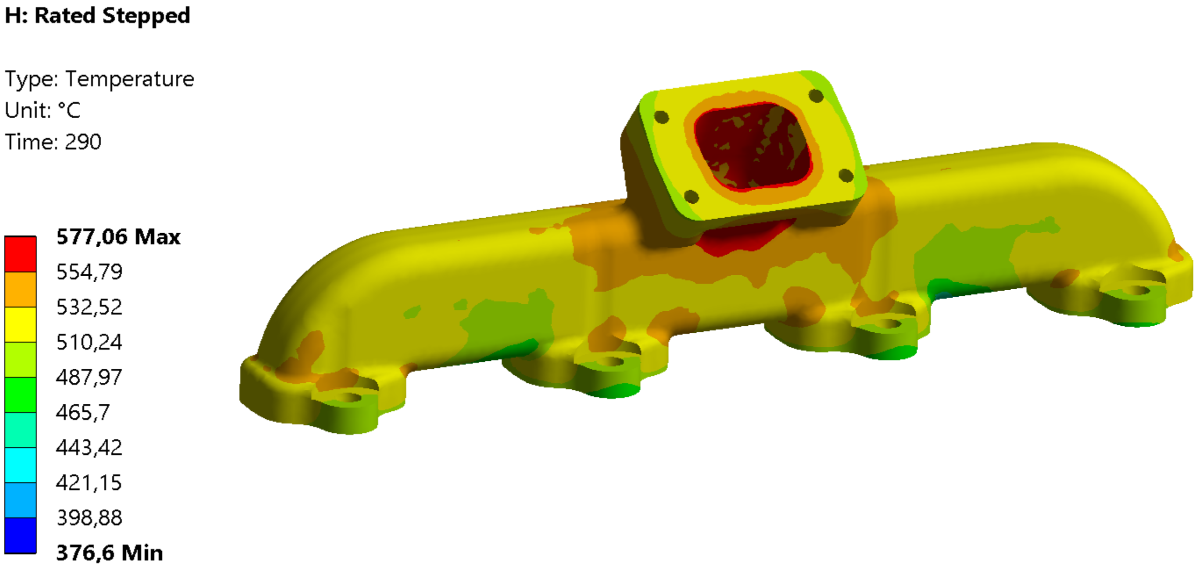

Figure 4.11. Exhaust manifold thermal analysis heat up phase

The state of the manifold, which has been exposed to heat when the engine operating iddle conditions again for a while, is available in the image below.

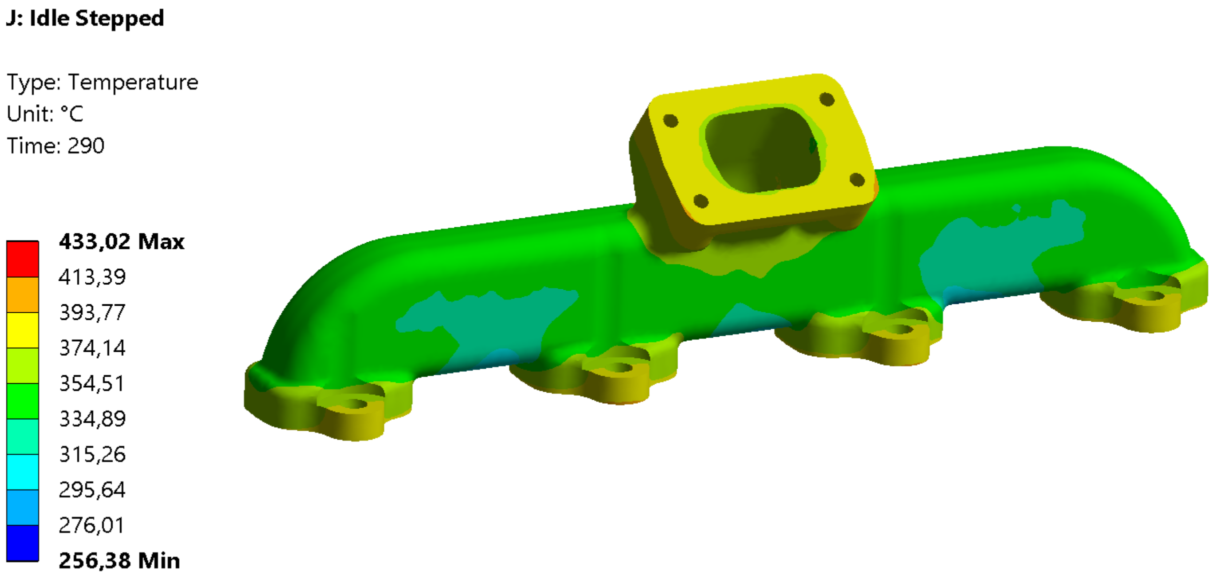

Figure 4.12 Exhaust manifold thermal analysis cool down phase

The heating and cooling phases to which the manifold is exposed, together with their levels, are available in the chart below.

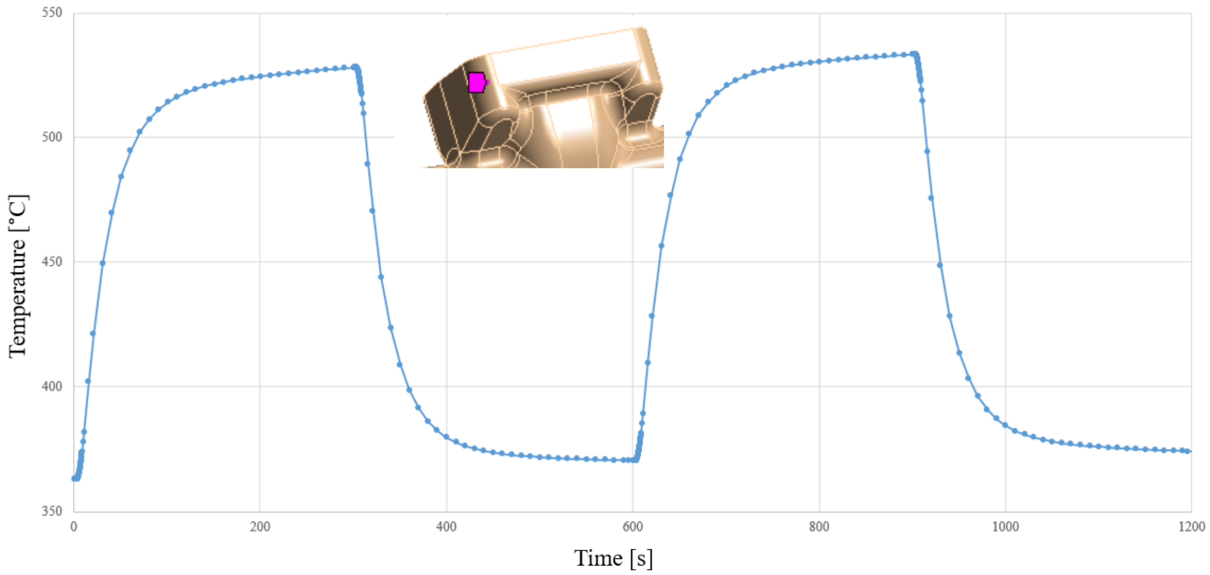

Figure 4.13. Exhaust manifold transient temperature variation

The temperature variation was get the corner of the turbo connection head, because corners anc neck regions are most exposed to heat.The temperatures from the full cycle are used as loads in the structural analysis.

4.2.1. Structural Analysis

The temperature distribution is displayed in Figure 4.14 following FEA study using Ansys software. The exhaust manifold engine head connection site exhibits maximum temperature values as would be expected.

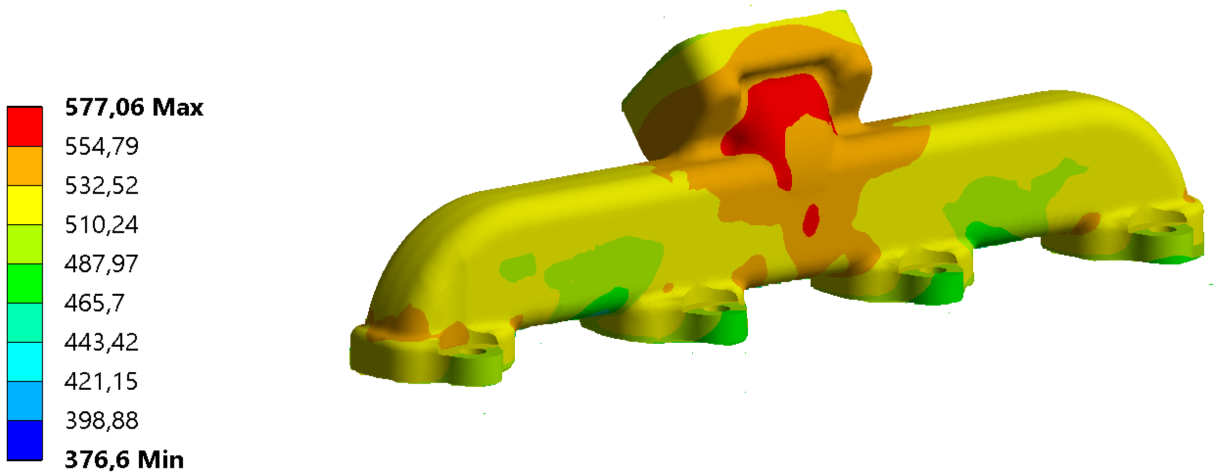

Figure 4.14. Exhaust manifold temperature distribution at the end of the heating step

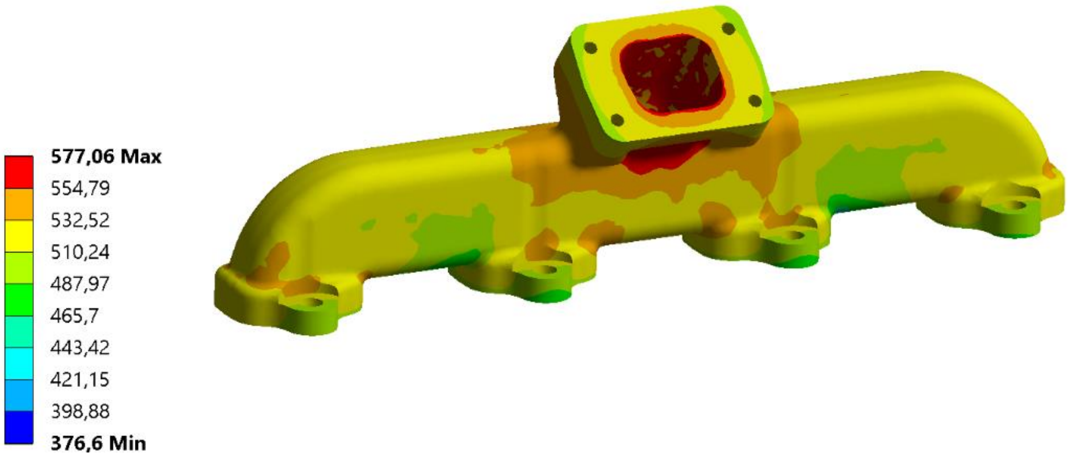

Figure 4.15. Exhaust manifold temperature distribution at the end of the heating step

For the purpose of simulating inelastic deformation and forecasting thermo-mechanical fatigue (TMF) failure, a temporary nonlinear Finite Element Analysis (FEA) is conducted. The highest Von-Misses Stress values for the heating and cooling phases are 253 Mpa and 219 Mpa, respectively. Locations where tensions build up can be shown as contours, as in Figure 4.16.

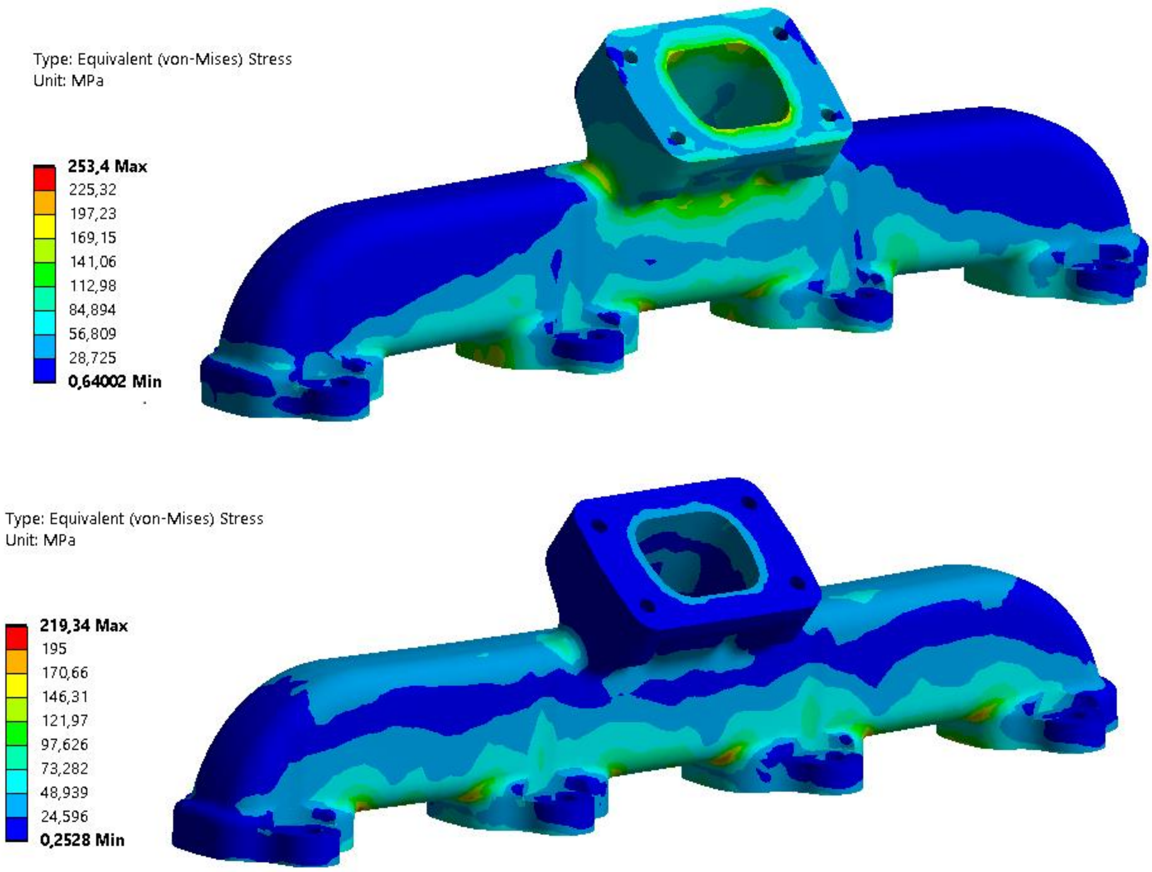

Figure 4.16. Von-Mises stress distribution for heating up and cooling down steps

In the images below, there are critical strain zones in the exhaust manifold as a result of the TMF analysis.

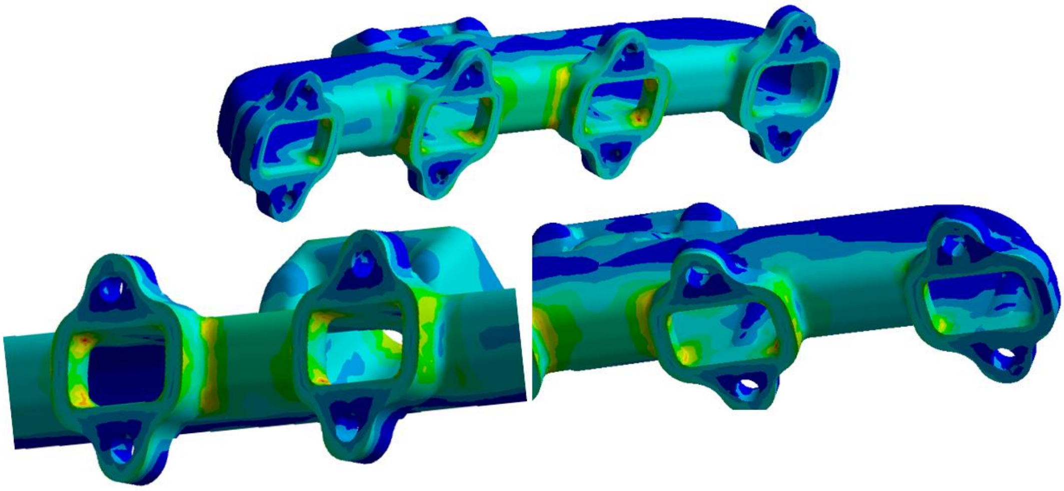

Figure 4.17. Stress accumulation areas of exhaust manifold

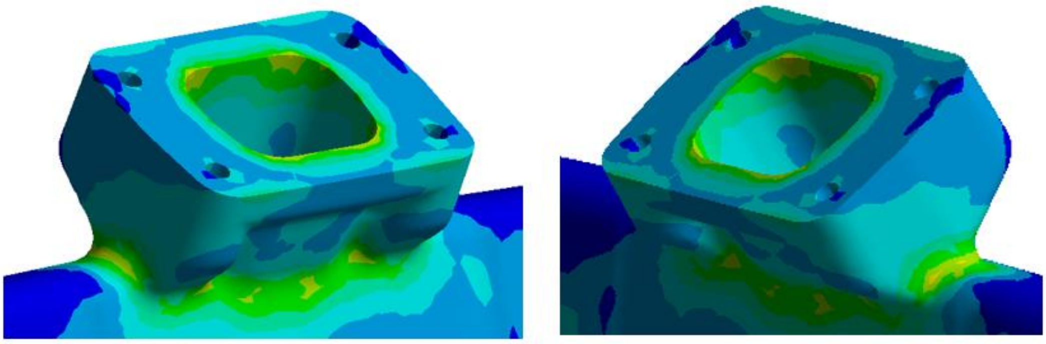

Figure 4.18. Stress accumulation areas of exhaust manifold neck region

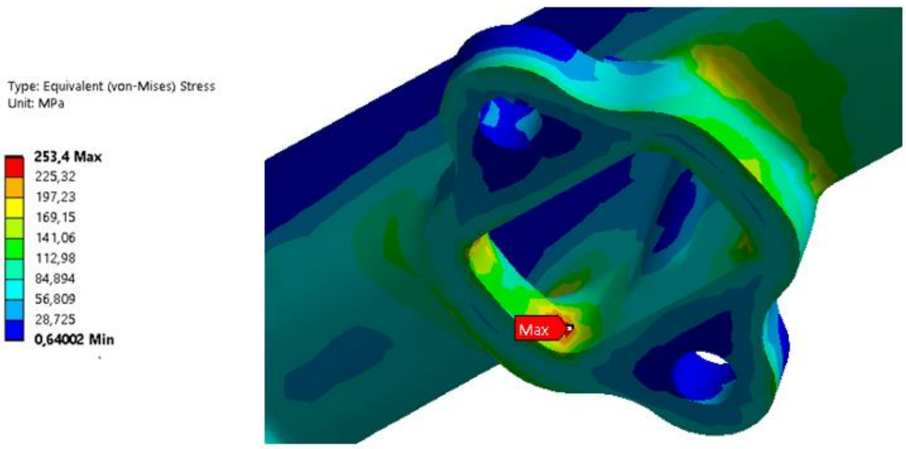

Figure 4.19. Maximum stress point of exhaust manifold

Structural analyzes show that in pick power condition, the stress occurs mostly in the regions where the gas passes from the cylinder to the exhaust manifold, which is 253 MPa. In the iddle conditions where the manifold is exposed, stess accumulation has occurred especially in the corner radiuses of the exhaust inlet ports where the gas passes from the cylinder to the manifold. The maximum stress in these regions is 219 MPa.

5. RESULTS AND DISCUSSIONS

In this study, theoretically thermal stresses of the exhaust manifold in the engine operating under different conditions are investigated.

The theoretical study in this thesis intends to examine the viability of CAE methodology utilized for the modeling of fluid flow in exhaust manifolds and the corresponding thermal distribution.

The purpose of making these analyzes is to catch the structural and design errors that can be detected before production. CFD and TMF theoretical analyzes of the designed exhaust manifold have been completed.

After defining boundary conditions, the analysis of the exhaust manifold, whose design was completed in the light of past experiences, started with CFD.

In this flow analysis for the designed exhaust manifold, no quality problems were found regarding the flow of the exhaust gas. While the expected values were observed in pressure drops and flow rates, changes that could be made in the exhaust manifold were determined to improve the flow. The most important of these changes is the reduction of the radius at the junction of the branches with the main flow branch, namely the turbo outlet region, on the wet surface. However, this situation is not acceptable as it is seen as inconvenient both in the casting process and in terms of strength. From the 3D fluid mechanics analysis, it was concluded that the current design can be continued without any changes.

The main findings of this CFD assessment study can be summarized as:

- 460 000 tetrahedral solution mesh was created.
- 0.9 skewness angle (measure of mesh quality) is provided.
- It has been observed that the heat transfer coefficient increases in parallel with the temperature in regions where the temperature is intense.
- In idle condition, the highest temperature of the wet surface was observed as 400 °C.
- In rated condition, the highest temperature of the wet surface was observed as 575 °C.

Thermal analyzes were run with the outputs of CFD analyzes. Thermal analyzes started by first identifying the conditions that the manifold might be exposed to in real life. Than the analysis heat up and cool down steps in Table 4.1 were applied to the manifold sequentially. In real life, the manifold is a component that heats up and cools down very quickly. The manifold eventually develops thermal accumulations on its walls because it operates at full load and is exposed to high temperatures.

In the thermal analysis, the regions with the highest thermal accumulation were generally the corner regions where the exhaust gas changes direction during the flow and the aggregation regions such as the turbo inlet with turbo inlet neck region. Therefore, it will be predicted that stress accumulation will occur in these regions. The maximum temperature achieved in these critical regions is 577 °C.

Structural analyzes were made with thermal analysis outputs.

For the life of the manifold, the skin temperatures are crucial. Considering the figures 4.17, 4.18 and 4.19 after the heating and cooling down phases of the exhaust manifold, the thermal stresses are mostly concentrated at the neck region of the turbo outlet and at the corner radius of the gas inlet ports. Maximum stress is 253 MPa for rated condition and maximum stress is 219 MPa for iddle condition for these regions. These stress levels are acceptable for the material selected for the manifold.

In the pipe line where the fluid passes, there may be situations where the fluid does not contact at the corner points or flows more slowly than at other locations. In the CFD analysis, thermal accumulation occurs more at these points than at other places. Because heat transfer develops more slowly at points where there is no contact or little contact. Therefore, stress can occur at these points.

When the results are compared with the results of M Kumara Varma et al, the temperature distribution is similar as seen in Figure 2.1. As can be seen in Figure 2.2, when the steady thermal stress calculation is compared, the stress accumulation point is similar, but when the maximum stress values are compared, results are visibly higher than the values in this study.

When the results are compared with the results of De Azevedo Cardoso et al, the temperature distribution also shows similarity as seen in Figure 2.3. However, as seen in Figure 2.2, when the exhaust failure point is compared, the stress accumulation point is at the engine block connection point in this study, while in our study it is at the corner radius of the gas inlet ports.

In Erken's study, in which the results of practical and theoretical experiments were compared, there was a 15% inconsistency between the actual experimental data and the theoretical experimental results. But this value was at an acceptable level.The thermal distribution map in Figure 2.5 and the Von-Mises stress distribution in Figure 2.6 show that Erken's experimental results and the theoretical experimental results and values in this study are similar, but differ in the points where the stress accumulation is highest.

Practical and theoretical experiments could not be compared in this study as there were no real experimental possibilities.

The design of the manifold is as important as the material selection for heat dissipation in the manifold and thermal stresses throughout the manifold. It is predicted that the thermal stresses will be high in the corner regions and the material thickness in the radius areas of these regions is slightly higher than the standard wall thicknesses.

On the basis of the collected heat data and fluid data, thermo-mechanical fatigue analysis is then completed. The percentage values of corresponding strains and creeping on the exhaust manifold are deducted after this cycle has been applied. The mentioned threshold amount may change depending on several factors.

The conditions under which the analysis will be performed, the thermal cycle that will be applied to the component, the computer software, the meshing technique and component software, and the methodology used to calculate the equivalent stress, strain, and creep values are just a few of the many variables that can affect the threshold value.

6. RECOMMENDATIONS

As mentioned throughout the research, the exhaust manifold is exposed to high temperatures during engine operation. During the heating and cooling phases, thermal stresses occur on the manifold. These stresses can cause serious damage to the manifold under high engine operating conditions. In order to prevent these damages, attention should be paid to the design, material selection and the correct selection of analysis conditions.

Since existing TMF models, including computer-aided engineering (CAE)software packages, are insufficient for the safety of crucial components, analysis alone is insufficient for thermal stress study. They are only models and frequently are unable to account for all the many TMF-related factors, including temperature, corrosion, residual stress, and variable amplitude loading. Thus, for the components that should have excellent fatigue value, analysis and testing are both necessary. Safety factors are frequently applied with or without the correct fatigue value. Too-low values may result in undesirable failures. Safety concerns should neither be used as a substitute for effective fatigue design methods or as an alibi for ineffective fatigue design procedures.

The circumstances for analysis and testing should be similar to those encountered in real workplace settings. In this investigation, it was necessary to make some assumptions and simplify things. Even while test results might not accurately reflect reality, they might nonetheless provide extremely near results.

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