RECREATION OF WATER-COOLED EXHAUST MANIFOLD TO IMPROVE EXHAUST GAS RECIRCULATION

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RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

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ABSTRACT

The exhaust manifold is a component of the common internal combustion engine designed to help flow the exhaust gases away from the cylinder. Usually attached onto the cylinder head with gaskets, nuts and bolts; modern technology has made it possible to integrate the exhaust manifold into the cylinder head. This results in a reduction of cost to manufacture or outsource gaskets, nuts and bolts; lower weight, volume and size; improved fuel consumption; and improved warm-up times from initial start-up. A functional method of improving emissions of an internal combustion is the introduction of recirculated exhaust gases for combustion. The system that incorporates this concept is called Exhaust Gas Recirculation. Traditionally, hot exhaust gas is fed into an EGR valve which regulates the amount of EGR into the intake of a diesel engine. This results in the reduction of NOx emissions due to the lower combustion temperature. Another use of EGR is to cool it and then introduce into the intake. This leads to an increase of engine efficiency due to the lower density of the air-fuel mix. However, modern Spark-Ignited engines have started to incorporate EGR to improve fuel consumption, part-load throttle performance and emissions. Modern engines also incorporate turbocharging, this therefore leads to further design variations in cooling the temperature of exhaust gas. This paper discusses the application of Exhaust Gas Recirculation, Cooled Exhaust Gas Recirculation, Integrated Exhaust Manifold and its concepts to recreate an exhaust manifold suitable for retrofitting onto existing engines of various applications. This exhaust manifold aims to reduce exhaust gas temperatures for the applications stated above to reduce heat transfer and stress on other existing systems while improving fuel consumption and emissions. This reduction in heat transfer to the other components in the engine bay can be attributed to the flow of fluid in the water-cooled exhaust manifold which extracts heat from the walls of the exhaust ports and into the fluid which will then be cooled by a radiator.

Keywords: Water-cooled Exhaust Manifold, Integrated Exhaust Manifold Cylinder Head, Exhaust Gas Recirculation, Internal Combustion Engine, emissions

ABSTRAK

Sebuah manifold ekzos ialah salah satu komponen sebuah enjin yang menggunakan proses pembakaran. Fungsi manifold ekzos ialah untuk mengalirkan gas ekzos dari enjin. Selalunya dipasang kepada kepala silinder enjin, teknologi moden telah merealisasikan penyatuan manifold ekzos dan kepala silinder enjin. Kesan daripada penyatuan ini ialah pengurangan kos kerana penghapusan kegunaan selak dan gasket; pengurangan berat, saiz dan isi padu; dan penambah baikan penggunaan bahan api. Salah satu cara untuk mengurangkan pelepasan NOx ke atmosfera ialah melalui EGR. EGR ialah pengedaran gas ekzos kepada cas udara dan bahan api untuk mengurangkan suhu pembakaran. Selain itu, penugrangan suhu EGR juga boleh menambah baik kesan-kesan EGR seperti penggunaan bahan api dan pengurangan pelepasaan bahan bahan toksik ke atmosfera seperti NOx dan CO. Dengan menggunakan konsep dari pelbagai teknologi seperti EGR, IEMCH dan ekzos yang disejukkan dengan air, sebuah reka bentuk boleh dicipta dengan fungsi untuk dipasang ke enjin-enjin yang sedang digunakan. Selain itu, kelebihan untuk pemasangan ciptaan ini boleh mengugrangkan kegunaan bahan bakar dan mengurangkan suhu gas ekzos untuk kurangkan tekanan haba kepada komponen komponen yang berada di kawasan enjin.

Kata Kunci: ekzos manifold yang disejukkan dengan air, penyatuan ekzos manifold Bersama kepala silinder, pengedaran semula gas ekzos, enjin pemabakaran dalam, pelepasan

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

CO	:	Carbon Monoxide
CO2	:	Carbon Dioxide
EGR	:	Exhaust Gas Recirculation
HC	:	Hydrocarbon
ICE	:	Internal Combustion Engine
IEMCH	:	Integrated Exhaust Manifold Cylinder Head
NOx	:	Oxides of Nitrogen

CHAPTER 1: INTRODUCTION

1.1 Background

Over the years, the concerns over air pollution and harmful emissions have increased due to negative impacts on the air quality which in return affects our health and quickens the process of global warming. This is due to the emissions constituting of toxic substances such as unburnt hydrocarbons, HC; carbon monoxide, CO; oxides of nitrogen, NOx. (Beychok, 1973)

Ideally, the combustion of the air-fuel mixture should convert the oxygen in the air and all the hydrogen in the fuel into water; oxygen in the air and all the carbon in the fuel into carbon dioxide; water and carbon dioxide being non-toxic emissions. However, realistic combustion of the air and fuel will release enough heat to make oxygen molecules interact with the nitrogen molecules to produce NOx. (E. Sendzikiene, 2006)

Many systems have been implemented to improve emissions of internal combustion engines such as variable valve timing (Hong, 2004), Gasoline Direct Injection (GDI) and Exhaust Gas Recirculation (EGR). Although the implementation of these systems has been applied in modern engines, further study should be conducted to implement an improvement in engine design to optimize the function of mentioned systems. However, in this research project, emphasis on heat loss wasted through cooling and exhaust gases will be given to turn cooling systems and exhaust systems beneficial to engine efficiency. This research project will study the effects of selected emission reducing methods in 4-Cylinder Internal Combustion Engines and design a system regarding the mentioned topics that are suitable for retrofitting onto existing engines of various applications.

1.2 Problem Statement

With the regulations in emissions becoming stricter over the years (Hoen, 2014), development in technology regarding the reduction of harmful emissions has matured. Examples of such technology are Exhaust Gas Recirculation, Integrated Exhaust Manifolds, Homogeneous Charged Combustion Ignition, and many more. However, there are many machineries that cannot implement certain technologies due to its application of older designs and technology. From extracting the advantages and disadvantages of various technologies, what is a cost-effective method of reducing the harmful emissions of existing machinery of various applications?

The overall objective of this project is to reduce harmful emissions of engines of various applications while prioritizing cost for the purpose of retrofitting onto already existing engines. To achieve this, the goals set are:

- Identify the advantages and disadvantages of Integrated Exhaust Manifold Cylinder Head.
- Identify the advantages and disadvantages of EGR and Cooled EGR.
- Analyze advantages and disadvantages of mentioned topics and create a system that achieves the goal.

The motive of this research is to recreate an exhaust manifold that incorporates cooling of exhaust gases by presence of water coolant jackets around the flow of exhaust gases. The recreation of the exhaust manifold instead of an entire cylinder head proves to be more cost effective.

The reality is most bodies and corporation wish to spend as little as possible to improve their emissions and fuel consumption. However, retrofitting new parts onto already existing machinery may reduce cost to make improvements on emission and fuel consumption a reality.

To achieve the goals of the project, several objectives have been set which are:

- Perform literature review on the technology applied in modern engines to reduce emissions (IEM, EGR and Water-Cooled Exhaust Manifold) and highlight important concepts to extract to recreate a water-cooled exhaust manifold
- Perform 3-D Modelling to recreate a water-cooled exhaust manifold which incorporates the concepts from the previously mentioned technologies and provide rendered models of various water-cooled exhaust manifold designs.
- Perform analysis on structural integrity and heat transfer flux between fluids in the recreated water-cooled exhaust manifold to ensure the designs are able to perform and extract heat successfully.

CHAPTER 2: LITERATURE REVIEW

2.1 Integrated Exhaust Manifold Cylinder Head

2.1.1 Background

Traditionally, the exhaust manifold is attached to the engine's cylinder head via gaskets, nuts and bolts. The gasket's purpose is to seal the manifold to the cylinder head to avoid any form of gas leakage while the nuts and bolts are used to help tighten the manifold to the cylinder head. However, with improvements in 3D modelling and manufacturing techniques, cylinder heads with more complex geometries can be produced. As a result, the concept of an exhaust manifold integrated into the cylinder head can be applied. This leads to differences in the typical arrangement of a cylinder. An Integrated Exhaust Manifold Cylinder Head (IEMCH) is able to be smaller in size when compared to the traditional exhaust manifold setup (Kuhlbach, 2009). This provides advantages such as space saving benefits in compact engine bays and weight saving benefits to lower a vehicle's center of gravity. An inherent design of the IEMCH is the coolant passages alongside the runners of the exhaust manifold that cool down the exhaust gases (Neshan, 2012).

2.1.2 Advantages

2.1.2.1 Reduced Parts Count

An obvious advantage of the IEMCH is the elimination of gaskets, nuts and bolts. This leads to less assembly procedures which reduces manufacturing costs of the assembly of a complete engine. The lower parts count also results in a reduction in size of the overall assembled engine. The reduced size will lead to improved space management in small vehicles which then eases the process of assembly of the vehicle. This then results in a simpler maintenance and servicing procedure. The elimination the gasket also results in the likelihood of exhaust gases to leak to reduce, further improving emissions. (D'Ambrosio, 2013)

2.1.2.2 Faster Engine Warm Up Time

Due to the coolant passage being designed along the exhaust runners, the coolant will come into close contact with the exhaust gas and as a result, heat exchange from the exhaust gas to the coolant will occur. This heat exchange can further decrease warm up time for the engine which results in the reduction of frictional losses. (Chen, 2016)

2.1.2.3 Improved Fuel Consumption and Emissions

To further improve warm up times and initial start-up emissions, the coolant flow can be regulated, and the exhaust gas temperature can remain high. This causes the catalytic converter to reach optimal temperature quicker. If exhaust gas temperature can be regulated appropriately, downsizing the catalytic converter may also reduce the time to reach optimum temperature to catalyze. Catalytic converters are produced with the inclusion of precious metals acting as the catalysts. Reducing the amount of these precious metals used will result in a further reduction in cost savings. (Turner, 2009)

2.1.2.4 Aluminum as Material Used

Regarding the literature concerning Integrated Exhaust Manifold Cylinder Heads, both papers discuss the benefits of the application of aluminum as the material used to produce the cylinder head. The use of aluminum was able to reduce the weight of the engine by 3.2 kg. The benefits of the weight reduction are lower center of gravity of the engine and the reduction of overall load (Neshan, 2012).

The thermal analysis regarding the thermal deformation of the IEMCH was also conducted. Replication of repeated thermal shock cycles, which is comprised of heating, powering and cooling stages, show that the aluminum structure of the cylinder head does not crack and deform making aluminum a reasonable material to use (Chen, 2016).

2.1.3 Disadvantages

2.1.3.1 Requirement of Improved Cooling System

Due to the design of the coolant passages along the exhaust runners, more heat will be transferred to the coolant due to the additional surfaces of the integrated exhaust manifold which results in larger heat energy stored. To overcome this issue, an improved cooling system is required. An improved or larger/more powerful water pump, radiator or fan will usually suffice. However, further modifications could also be done on the design of the IEMCH to incorporate fins to reject heat from the coolant and into the surrounding if necessary (D'Ambrosio, 2013).

2.2 Exhaust Gas Recirculation

2.2.1 Background

The concept of recirculating exhaust gases into the intake is to dilute the oxygen present in the air-fuel mixture and provide inert compounds and gases to absorb the excess heat of the combustion to lower the combustion temperature. The simplest forms of EGR were as simple as attaching a loop from the exhaust manifold directly into the intake manifold, with minimal forms of control and regulation. (Agarwal, 2011)

2.2.2 Advantages

2.2.2.1 Reduction of NOx

NOx is formed by the nitrogen and excess oxygen of the air-fuel mixture. Since nitrogen is an inert gas, it does not usually react in the combustion. However, due to the high release of energy after combustion, nitrogen is able to form NOx with oxygen due to combustion temperatures of 1600 Celcius or in excess (Palash, 2013). The following is the thermal formation of NOx due to the presence of nitrogen in air:

$$N2 + O \rightleftharpoons NO + N$$

$$N + O_2 \rightleftharpoons NO + O$$

$$N + OH \rightleftharpoons NO + H$$

NOx is a harmful pollutant and emissions of it should be reduced. Reduction of NOx can be achieved through the introduction of recirculated exhaust gases into the intake with the help of Exhaust Gas Recirculation systems (Ladommatos, 1996). The setup of EGR systems may vary from engine to engine but the common premise is the use of an EGR valve to control the amount of EGR to be mixed with the air-fuel mixture.

Since exhaust gas is generally composed of water vapor and carbon dioxide, which have lower specific heat capacities than air, the application of EGR will reduce the temperature and pressure of the combustion mixture during the isentropic compression in the combustion chamber, which results in lowering the combustion temperature of the adiabatic flame (Zheng, 2004).

2.2.2.2 Reduction of CO

An initial method of reducing the combustion temperature is by adding more fuel to the mixture. However, the addition of excess fuel causes the formation of carbon monoxide. Carbon monoxide is formed when there is not enough oxygen to produce CO_2. With the introduction of EGR, the need to add excess fuel is obsolete (Plessing, 1998).

2.2.2.3 Reduction of Knock

With the introduction of EGR in spark-ignition engines, the air-fuel mixture reaction rates reduce to result in longer burning rates. These longer burning rates lead to more predictable and controlled combustion. This further relates to the suppression of knock. With the suppression of knock, the timing of the spark for ignition can be advanced and optimized to improve. This can result in increased engine efficiency and reduced fuel consumption (Abd-Alla, 2002).

2.2.2.4 Variety of Applications

(a) ***Naturally Aspirated Internal Combustion Engines***

The application of EGR systems in naturally aspirated ICE is usually straightforward due to the high backpressure in the exhaust manifold when compared to the pressure in the intake manifold. This pressure difference is enough to drive the exhaust gases to a desired amount. Once an appropriate flow passage is created, the exhaust gases entering the intake manifold will be regulated by an EGR throttling valve. (Zheng, 2004)

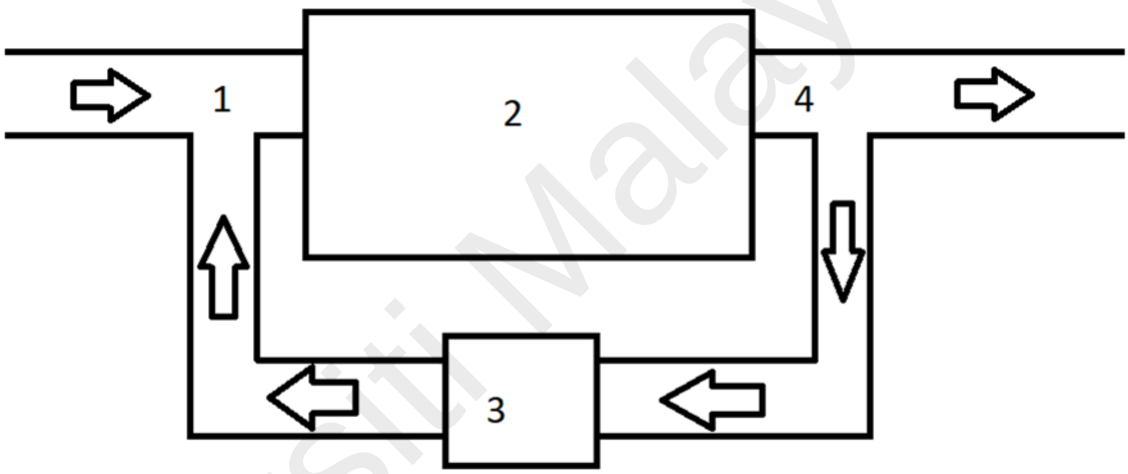

Figure 2.1: Simple EGR Diagram

Table 2.1: Numbering & Component Name for Simple EGR

Number	Component Name
1	Intake
2	Engine
3	EGR Valve
4	Exhaust Manifold

*(b) **Turbocharged Internal Combustion Engines***

The application of EGR systems in turbocharged ICE can be categorized into two loops: High Pressure Loop and Low Pressure Loop.

Low Pressure Loop is when the EGR valve is fed with exhaust gases after the turbine of the turbocharger. The EGR valve will then feed the intake before the compressor recirculated exhaust gases (Grondin, 2009)

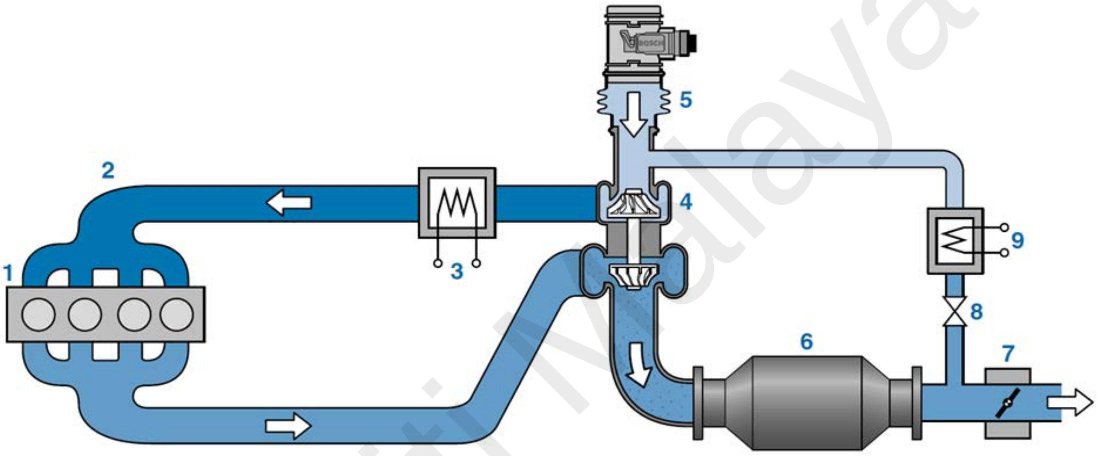

Figure 2.2: Diagram of LPL

Credit: Bosch

Table 2.2: Numbering & Component Name for LPL

Number	Component Name
1	Engine
2	Intake
3	Intercooler
4	Compressor
5	Mass Air Flow Sensor
6	Catalytic Converter

7	Exhaust System Butterfly Valve
8	EGR Valve
9	EGR Cooler

High Pressure Loop is when the EGR valve is fed with exhaust gases before the turbine of the turbocharger. The EGR valve will then feed the intake after the compressor recirculated exhaust gases (Wei, 2012).

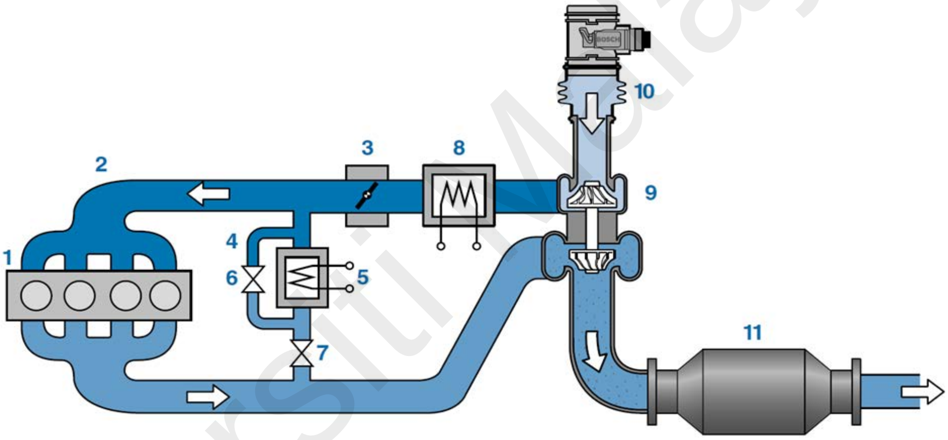

Figure 2.3: Diagram of HPL

Credit: Bosch

Table 2.3: Numbering & Component Name for HPL

Number	Component Name
1	Engine
2	Intake
3	Intake System Butterfly Valve
4	Hot EGR Route

5	EGR Cooler
6	Secondary EGR Valve
7	Primary EGR Valve
8	Intercooler
9	Compressor
10	Mass Air Flow Sensor
11	Catalytic Converter

2.2.3 Disadvantages

2.2.3.1 Beneficial At Specific Loads

Without the application of EGR, the exhaust gases of energy efficient Diesel engines usually contains oxygen at 5% under full load and at 20% under idling conditions (Maiboom, 2008). Since there is less oxygen in the exhaust gas at higher loads, this means that the specific heat of the exhaust increases because of the excess oxygen is reacting to produce CO2 (Agarwal, 2011)

This variation in the specific heat capacity of the exhaust means that with the application of EGR, NOx reduction is dependent on the load of the engine. At high loads, the addition of EGR will increase the overall specific heat capacity of the mixture due to the higher percentage of CO2 in the exhaust, ultimately lowering the maximum temperature of the working fluid. This reduces the formation of NOx but sacrifices power output due to the inert compositions in the exhaust gas being too dominant over oxygen, making it difficult for combustion (Saichaitanya, 2013)

2.2.3.2 Uncontrolled EGR Components

For diesel engines, the exhaust gases usually contain materials that are corrosive and abrasive in property such as sulfuric salts. The reintroduction of these substances in the combustion will ultimately deteriorate internal engine components. Deterioration can start with the pollution of the intake manifold which would cause irregularities in the manifold flow resulting in power loss. Then it may move to the combustion chamber where these abrasive and corrosive substances could wear down the cylinder lining and piston rings which results in higher friction and lower efficiency. This would affect the turbocharger's turbine (Amann, 2011)

2.3 Cooled Exhaust Gas Recirculation

2.3.1 Background

Since the purpose of EGR is to reduce the overall combustion temperature to reduce the production of NOx, reducing the temperature of the exhaust gases will also reduce the emissions of NOx. This happens because the when cooling the EGR, the density of the EGR increases. This results in the increase of mass flow rate in the intake charge, which shares a similar concept to boost inter-cooling of a turbocharger (Potteau, 2007).

To reduce the temperature of the EGR, an EGR cooler is installed before the EGR valve. The EGR cooler is fed with coolant in order to remove heat from the exhaust gas.

2.3.2 Advantages

2.3.2.1 Further Reduction in NOx Emissions

Studies have shown that when leaning the air-fuel mixture and advancing spark timing, which is due to less components in the air to absorb the heat from combustion, ultimately increasing NOx emissions. However, the addition of cooled EGR has resulted in a further reduction in NOx emissions, meaning that the cooled EGR has more impact than the other variables (Zelenka, 1998) .

2.3.2.2 Further Prevents Knock

Cooled EGR can further reduce the combustion temperature which leads to a reduction in the likelihood of knock to occur. This can be achieved because of two components: basic reintroduction of EGR into the air-fuel mixture and the cooled aspect of the EGR. As mentioned before, EGR contains components that are inert and are able to absorb the heat of combustion. The cooled aspect of EGR is the overall increase of density of the EGR which leads to the further increase of the specific heat capacity of the combustion charge (Grandin, 1998).

2.3.2.3 Application at High Loads

Studies have shown that if hot exhaust gas is recirculated directly into the intake, the cylinder charge temperature will be slightly above the temperature of the EGR at higher loads. This leads to a rise in the working fluid temperature which results in a less effective way of reducing NOx emissions, alternating to fuel enrichment instead which results in higher fuel consumption (Su, 2014).

However, with the introduction of an EGR cooler to reduce the temperature of the recirculated exhaust gas at higher loads, this will reduce the cylinder charge temperature and result in the lowering of the working fluid temperature. This results in the reduction of NOx emissions and prevention of knock.

2.3.3 Disadvantages

2.3.3.1 High Values of HC in Exhaust Gas

Hydrocarbons are harmful emissions classified as burnt or partially burnt fuel and are considered toxic. Hydrocarbon is proven to be a large contributor to smog which is an unresolved issue in urban areas with high traffic.

Hydrocarbons are components from the fuel in the air-fuel mixture. However, with the introduction of EGR to reduce the temperature of combustion and further cooled to increase density of the mixture, this leads to an occurrence of more incomplete combustion. More incomplete combustion results in the increase of the emissions of hydrocarbons (Feng, 2018).

2.4 Direct Comparison of Hot EGR vs Cold EGR

2.4.1 Brake Thermal Efficiency

Generally, the higher the load, the higher the value brake thermal efficiency. Therefore, the maximum value for the thermal efficiency will be at the maximum load (Alger, 2012). When the EGR rate is increased, the brake thermal efficiency is slightly increased. It is proven that under specific design conditions, 10% cold EGR can has the highest BTE at partial loads. However, under the same conditions, 15% hot EGR has the highest BTE at higher loads (Saichaitanya, 2013). This is because internal combustion engines will have higher intake temperatures, the higher the load due to the higher velocity and pressure. This higher temperature will then speed up combustion velocity which then increases the brake thermal efficiency. Higher EGR rates will result in the reduction of brake thermal efficiency.

2.4.2 Brake Specific Fuel Consumption

Generally, the brake specific fuel consumption decreases when the load increases. However, with the addition of EGR into the mixture, the BSFC increases across the load range (Bozza, 2016). Under specific design conditions, it is shown that a 15% hot EGR introduction provides slightly higher BSFC values than 10% cold EGR (Saichaitanya, 2013).

2.4.3 Exhaust Gas Temperature

As the load increases, the exhaust gas temperature increases as well. However, the increase of EGR rates into the air-fuel mixture is able to decrease the exhaust gas temperature. Further reduction in temperature can be achieved by lowering the temperature of the EGR (Hountalas, 2008). Under specific design conditions, it is proven that rates of 10% and 15% of hot EGR is less effective to reduce exhaust gas temperatures than rates of 10% and 15% of cooled EGR (Saichaitanya, 2013).

2.4.4 Carbon Monoxide Emissions

As the load increases, the CO emissions also increase. The cause of the formation of CO is the incomplete combustion of the air-fuel mixture due to an excess of fuel or a restricted supply of air. Typically, a rich fuel mixture is used for combustion to reduce the exhaust gas temperature. However, when replacing the excess fuel with EGR, the CO emissions decrease. Under specific design conditions, it is proven that rates of 10% and 15% of cooled EGR is more effective to reduce emissions of CO than rates of 10% and 15% of hot EGR (Saichaitanya, 2013).

2.4.5 NOx Emissions

NOx is formed by the nitrogen and excess oxygen of the air-fuel mixture. Since nitrogen is an inert gas, it does not usually react in the combustion. However, due to the high release of energy after combustion, nitrogen is able to form NOx with oxygen due to high combustion temperatures (Maiboom, 2008). With EGR introduced, the combustion temperature reduces. Managing to reduce this temperature decreases the emissions of NOx. Under specific design conditions, cooler and higher EGR rates prove to be more effective in reducing NOx emissions followed by 10% cooled EGR, 15% hot EGR then 10% hot EGR (Saichaitanya, 2013).

2.5 Liquid Cooled Exhaust Manifolds

2.5.1 Background

Liquid cooled Exhaust Manifolds are exhaust manifolds with a water jacket surrounding the runners of the exhaust. Liquid Cooled Exhaust Manifolds are used in a variety of applications ranging from industrial purposes to military purposes.

2.5.2 Application

For industrial applications, liquid cooled exhaust manifolds are used to reduce the temperature of the exposed surface of the manifold. This is usually for safety aspects as to reduce the possibility of fire hazards (Scheeringa, 2002).

For automotive applications, liquid cooled exhaust manifolds also share the same purpose as that of the industrial purpose, in addition to lowering the heat rejected to the surrounding. This is to reduce thermal stress on composite components in the engine bay (Milanovic, 2003)

For propulsion applications, liquid cooled exhaust manifolds are used to lower the exhaust gas temperatures. This is because it is used in conjunction with EGR to further reduce NOx emissions (Taylor, 2010).

For military applications, liquid cooled exhaust manifolds share the same purpose as automotive purposes, but instead of reducing thermal stress, the lower heat rejected is used to control the infrared signature of marine vessels to avoid tracking and detection from the enemy (He, 2012) (Dymarski, 2016).

2.6 Literature Review Summary

To summarize, the technologies and systems applied in modern engines that were discussed were IEM, EGR (and Cooled EGR) and Water-Cooled Exhaust Manifolds. IEMs are able to reduce emissions through the elimination of gaps and gaskets between the contact of the exhaust manifold and the cylinder head while reducing size and cost of manufacturing. EGRs are able to reduce harmful emissions by engines by reducing the formation of NOx emissions which is achieved through the lowering of temperature of combustion by reintroducing exhaust gases into the intake. Water-Cooled Exhaust Manifolds are beneficial due to the lowering of exhaust gas temperatures by having fluid flowing through the manifold extract heat from the exhaust gases through conduction and convection.

CHAPTER 3: RESEARCH METHODOLOGY

The methodology for this research project will be according to the following flow chart. Starting with Initial Research and ending with Project Discussion.

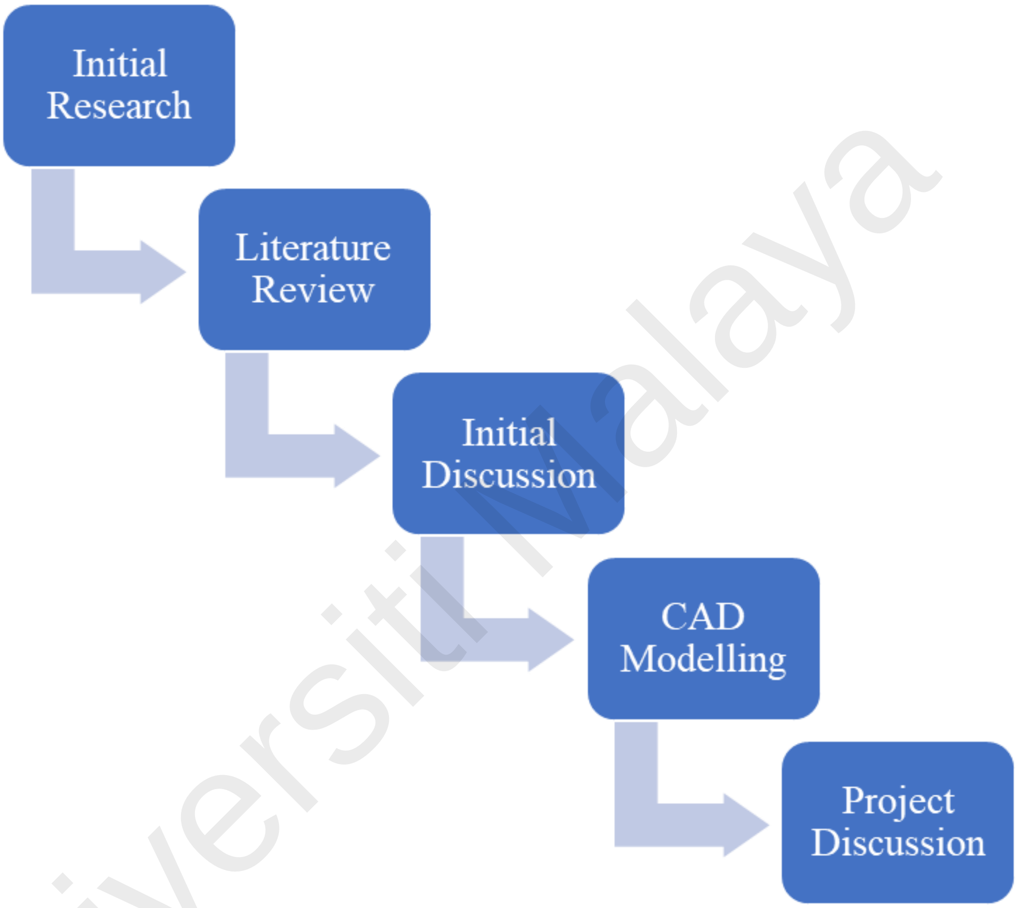

Figure 3.1: Flow Chart of Project

3.1 Initial Research

Research on the contributing factors of air pollution and emissions is carried out. Then, highlight the factors that are low cost and can be easily integrated into current automotive applications.

3.2 Literature Review

Conduct further literature review to improve comprehension on IEM, EGR, and cooled EGR. Analyze advantages and disadvantages of the applications of the mentioned systems. Then, create a system that incorporates advantageous concepts of each of the mentioned systems.

3.3 Initial Discussion

Incorporate concepts from already existing technology into a component easily attached onto existing machinery. Then, highlight advantageous previously mentioned to meet the goal of the project.

3.4 CAD Modelling

The CAD Modelling software that was used was Autodesk Inventor Professional Student Edition 2021. It was used for the creation of an exhaust manifold with basic geometry. Then, a creation of improved exhaust manifold with inlet for EGR valve. Next, an improvement of the previous concept with tubed coolant passages. Then, an improvement of the previous concept with finned surfaces. Finally ending with a refined water-cooled exhaust manifold with integrated inlets for sensors, external devices (such as EGRs, and coolant).

3.5 Project Discussion

A brief description on component created and its various concepts. Then the highlighted concepts were taken and applied into the component. Then, a discussion on the design limitations of the component. Next, a discussion on the applications of the component. Finally, a discussion on the limitations faced during the duration of the project.

CHAPTER 4: DISCUSSION

4.1 Literature

Under this section, the findings from the literature review were analysed and the advantages and disadvantages highlighted in this section will be in the perspective of the research project’s goal of a recreation of an exhaust manifold.

4.1.1 Integrated Exhaust Manifold Cylinder Head

4.1.1.1 Advantages

Integrated Exhaust Manifold Cylinder Heads are overall smaller in size compared to an exhaust manifold attached to a regular cylinder head. This leads to a more compact design suitable for smaller engine bays. This smaller and integrated design also provides a reduction in manufacturing costs due to the elimination of exhaust manifold gaskets, nuts and bolts. This leads to less processes requiring human resources which results in a simpler process of servicing and maintenance, which further reduces lifetime costs.

Previously mentioned was the elimination of gaskets, nuts and bolts. This means that this will reduce the likelihood of exhaust leaks. This also leads to improved catalyst performance, and if designed appropriately, the catalyst is able to use less precious metals and materials which lowers the manufacturing cost of the vehicle.

The coolant passages and exhaust runners of an IEMCH is designed in a way that there is heat exchange from the exhaust gases to the coolant. With a way to control the flow of coolant, the engine will be able to heat up faster resulting reduced frictional losses and reduced fuel consumption and emissions at cold start.

4.1.1.2 Disadvantages

The first disadvantage regarding the scope of this project is that it is not feasible for application onto existing engines. While production of a brand-new engine incorporating modern and improved technology is one of the solutions to reducing emissions, the underlying issue is concerning the already existing engines that have been used by the consumers. Manufacturing brand new cylinder heads will need plenty of cost, effort, and time to be applied to a variety of engine blocks.

The next disadvantage is the requirement of improved cooling system. One of the benefits of the integrated exhaust manifold is the lowered exhaust manifold wall temperature. This is also partly due to the coolant extracting the heat and away from the exhaust gases. The heat extracted then leads to a higher coolant temperature which then requires an improved radiator and fan to lower the coolant temperature.

4.1.2 Hot and Cold EGR

4.1.2.1 Advantages

The first advantage regarding the scope of the research project is the improved engine performance, fuel consumption and emissions. Reducing NOx is necessary to meet regulation standards. Traditionally, the emission of NOx can be reduced by the addition of extra fuel into the combustion chamber to lower the flame combustion temperature. However, with the introduction of recirculated exhaust gases into the intake, this then reduces throttling at part load range which then reduces fuel consumption and the production of NOx. This is due to the characteristics of the recirculated gas introduced in the intake with both hot and cold EGRs providing benefits.

The next advantage is that it is a small separate & independent system. The setup of an EGR system is theoretically simple: an EGR valve is connected to the exhaust manifold via metal tubing; the EGR valve controls the flow of the exhaust gases; it is then connected to tubing that leads to the intake manifold and enters the combustion chamber when the intake valve opens. However, several adjustments can be made like finding the optimum location to extract the exhaust gases from the manifold or how the EGR will be reintroduced into the combustion chamber. These adjustments should be made to further improve the combustion chamber mixture properties. EGR coolers should also be attached before the EGR valve to reduce the temperature and increase the density of the exhaust gas. Due to the described characteristics, minimal modifications are needed to be applied to a variety of existing engines.

4.1.2.2 Disadvantages

The disadvantage that EGR may have is that it may negatively impact engine performance and emissions. Uncontrolled EGR can cause instability at idle or high loads. This instability is due to the actual properties of the air-fuel mixture, since the EGR reduces the combustion rate, stable combustion is harder to achieve. Also, if the EGR is not filtered properly, it may have extra particulates in the exhaust gas such as excess unburnt fuel and will cause uncertainty during operation.

4.1.3 Water-Cooled Exhaust Manifolds

4.1.3.1 Advantages

As previously mentioned, water-cooled exhaust manifolds are able to reduce the amount of rejected heat from the surrounding. This can reduce thermal stress and wear on components in the engine bay that are sensitive to heat.

The same concept has been applied in the aviation industry where EGR is used in conjunction with the water-cooled exhaust manifold to lower exhaust gas temperatures for recirculation.

4.1.3.2 Disadvantages

One of the disadvantages of water-cooled exhaust manifolds are that it requires more resources to lower the temperature of the coolant to extract heat from the exhaust gas. This leads to a requirement in a more efficient and powerful cooling system.

4.2 Design

4.2.1 Background

The purpose of the recreation of the exhaust manifold was due to the already existing engines around the globe. Most of these engines have outdated emission reduction technology and the application of EGR systems is one of the most cost-effective methods to meet modern emission regulations. A step to meet modern emission regulations for these cars is to apply small, separate and independent systems and technology onto these engines. Having coolant passages run along the exhaust flow is a concept taken from integrated exhaust manifold cylinder heads and having these coolants reduce the exhaust gas is a concept taken from cooled EGR.

The recreated exhaust manifold incorporates coolant channels with hopes of reducing the temperature of the exhaust manifold wall. With the hopes of reducing the temperature of the wall, this would translate to lower exhaust gas temperatures when reaching the EGR valve in hopes to achieving a similar result to cooled EGR systems. This in turn can reduce thermal stress on the EGR components, reduce thermal stress on forced induction components, reduce the sizing of catalytic converter, and improve start up times of the engine.

Due to the lower exhaust gas temperatures, this results in lower heat rejected into the surroundings. This is beneficial for automotive purposes due to the usual compact engine bay with many parts being composite, plastic or material that has low density and low specific heat capacity. This would further improve the longevity of those components and reduce service schedules.

The hotter the exhaust gas, the more surface area and volume is needed from a catalytic converter to absorb the heat from the exhaust gas. However, the larger the surface area and volume of the catalytic converter, the time for the catalytic converter to achieve optimum temperature to catalyse the exhaust gases. With lowered exhaust gas temperatures, the sizing of the catalytic converter can be reduced and in return will improve the time to reach optimum operating temperatures. This in turn reduces the pollution during start-up of the engine.

The improvement of start-up times can also be achieved through the flow of the coolant itself. Since the coolant that flows through the recreated exhaust manifold is sourced from the coolant tank and radiator, the flow of coolant that is shared in the radiator will also rise in temperature quickly due to close contact with the exhaust gases.

4.2.2 Rendered Models

Several basic models were rendered to help with a rough visualization of the recreated manifold.

The first model (EM1) was created only with the exhaust passage to highlight the application of its generic shape for different uses of engine sizes and placement of coolant passages.

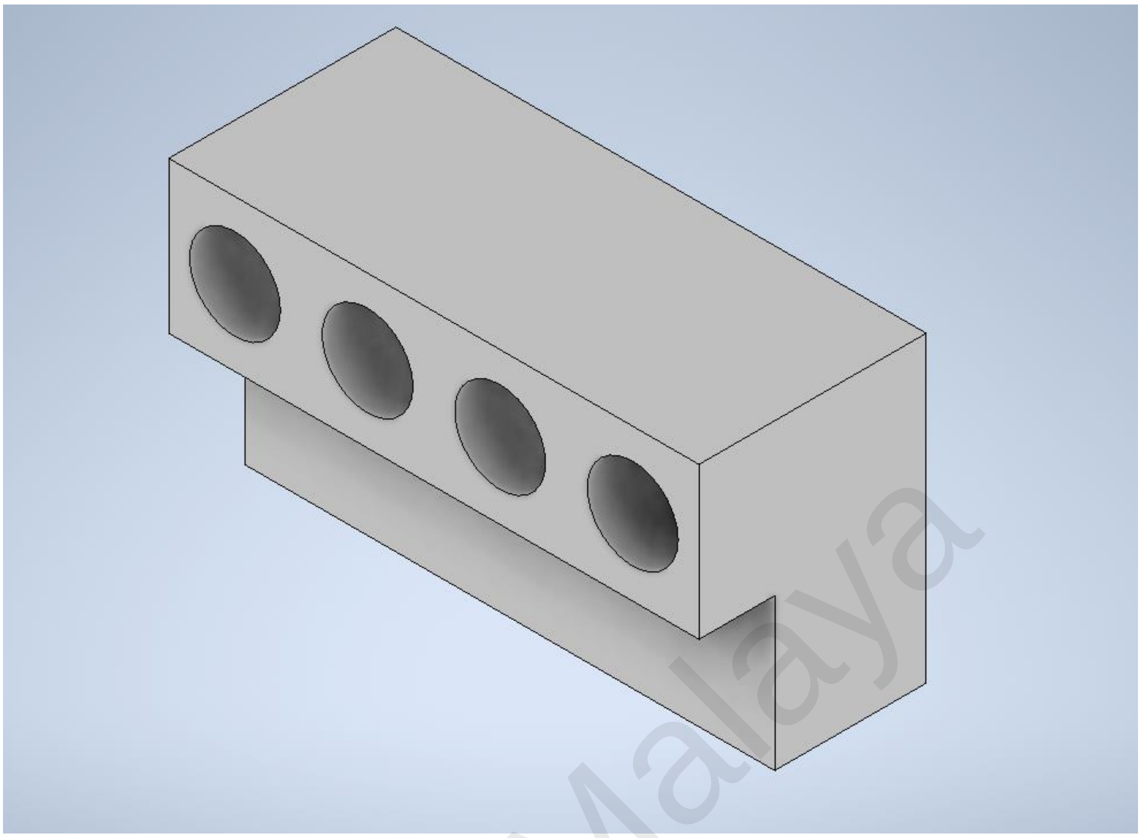

Figure 4.1: EM1 Main View

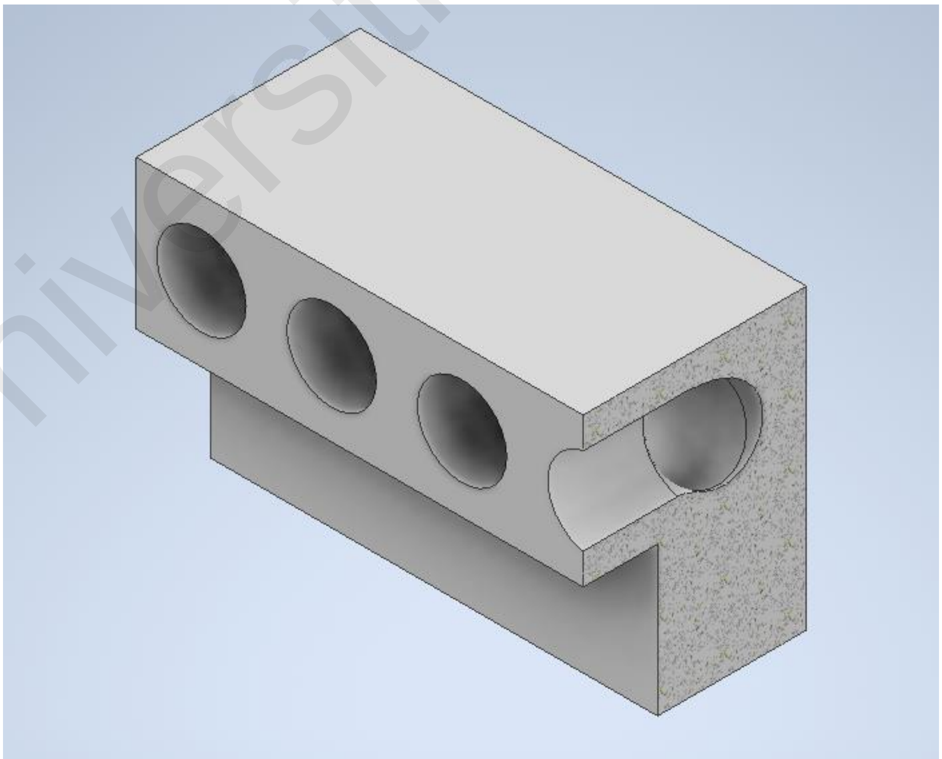

Figure 4.2: EM1 Cross Section 1

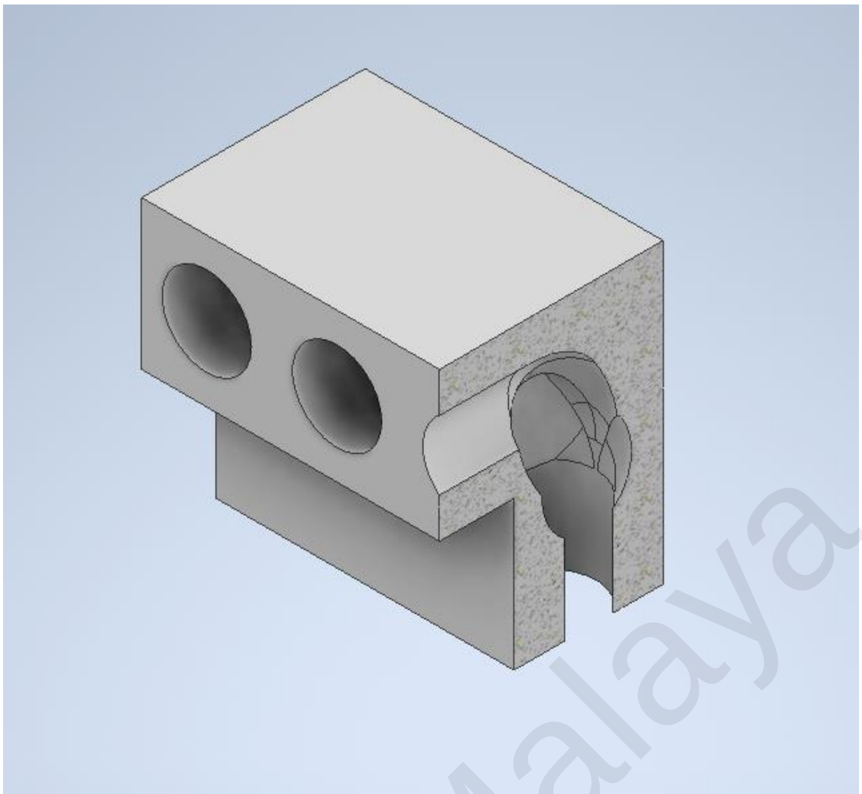

Figure 4.3: EM1 Cross Section 2

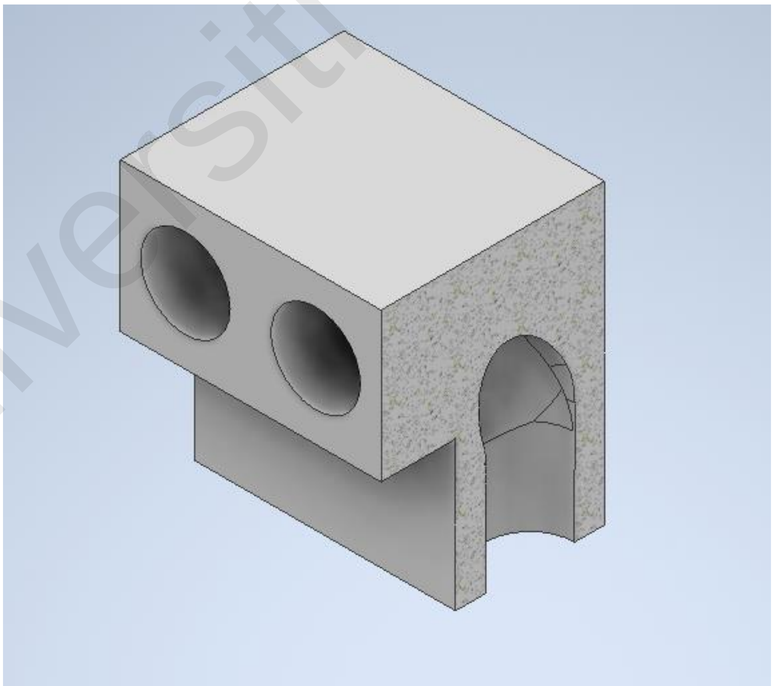

Figure 4.4: EM1 Half Section

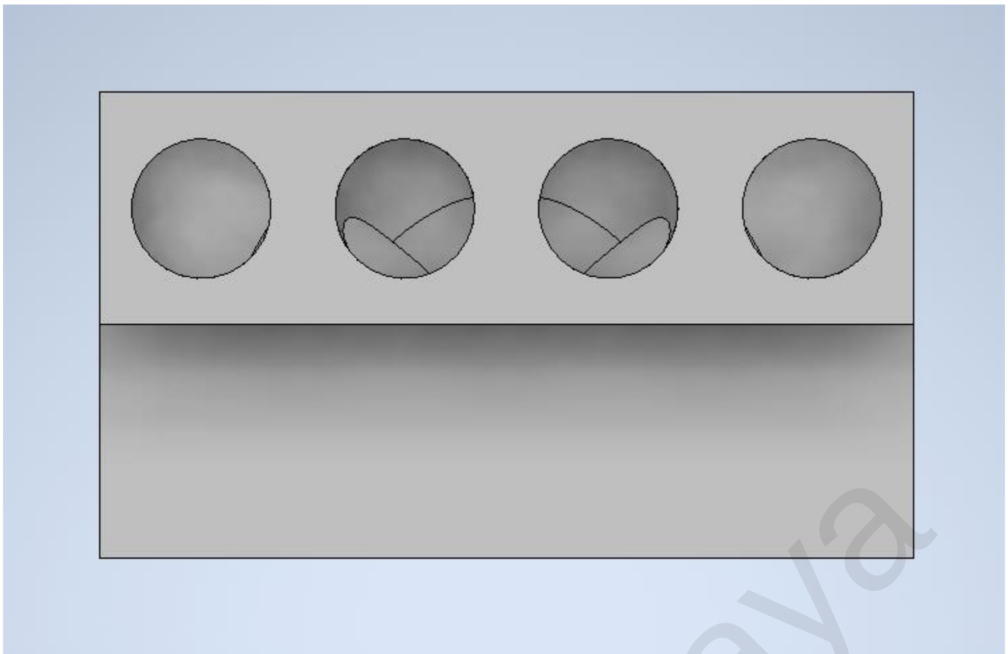

Figure 4.5: EM1 Front View

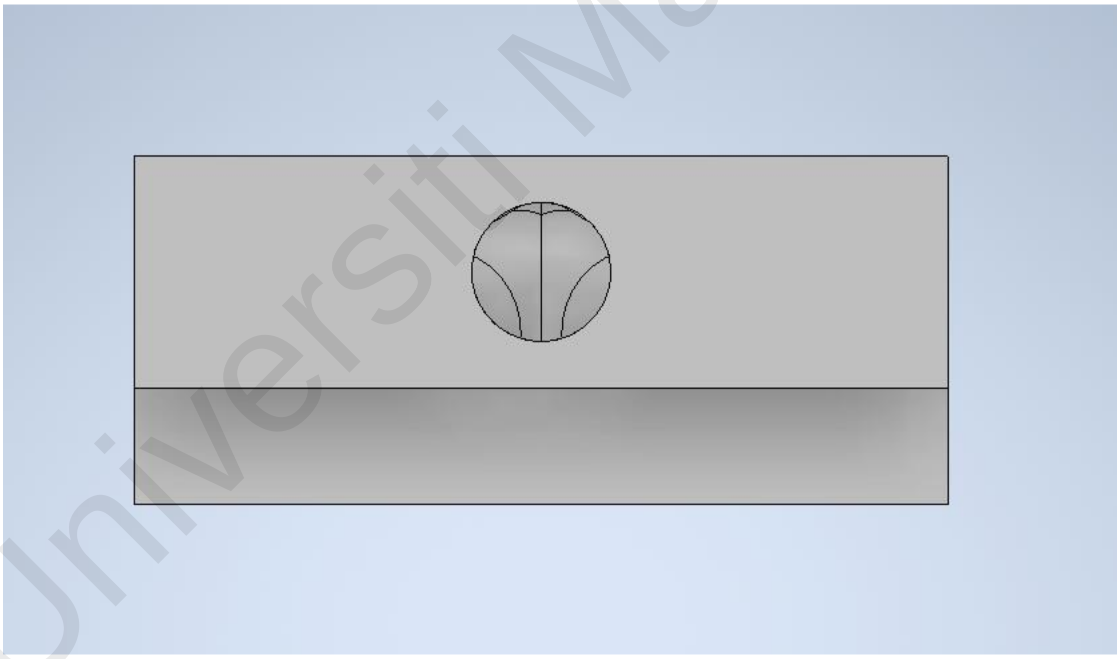

Figure 4.6: EM1 Bottom View

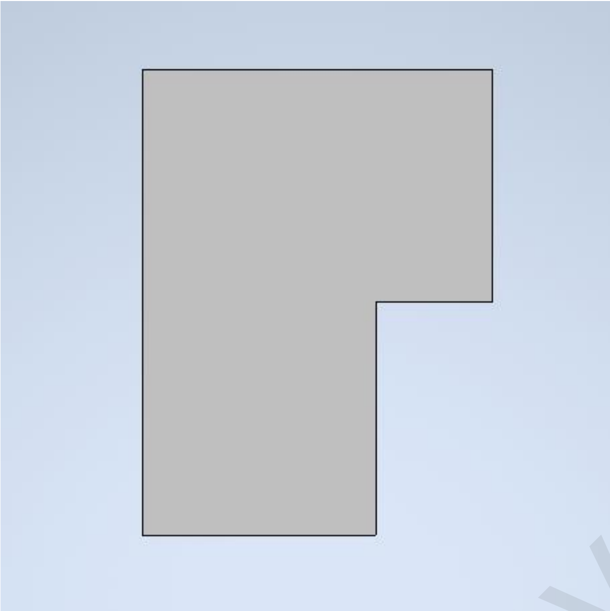

Figure 4.7: EM1 Side View

Figure 4.8: EM1 Back View

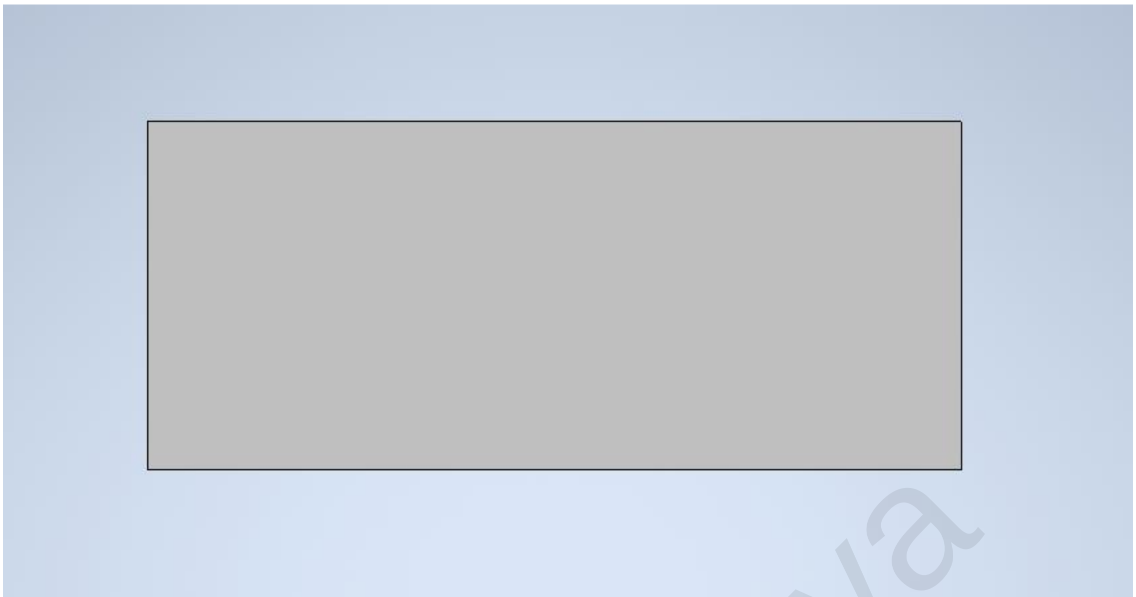

Figure 4.9: EM1 Top View

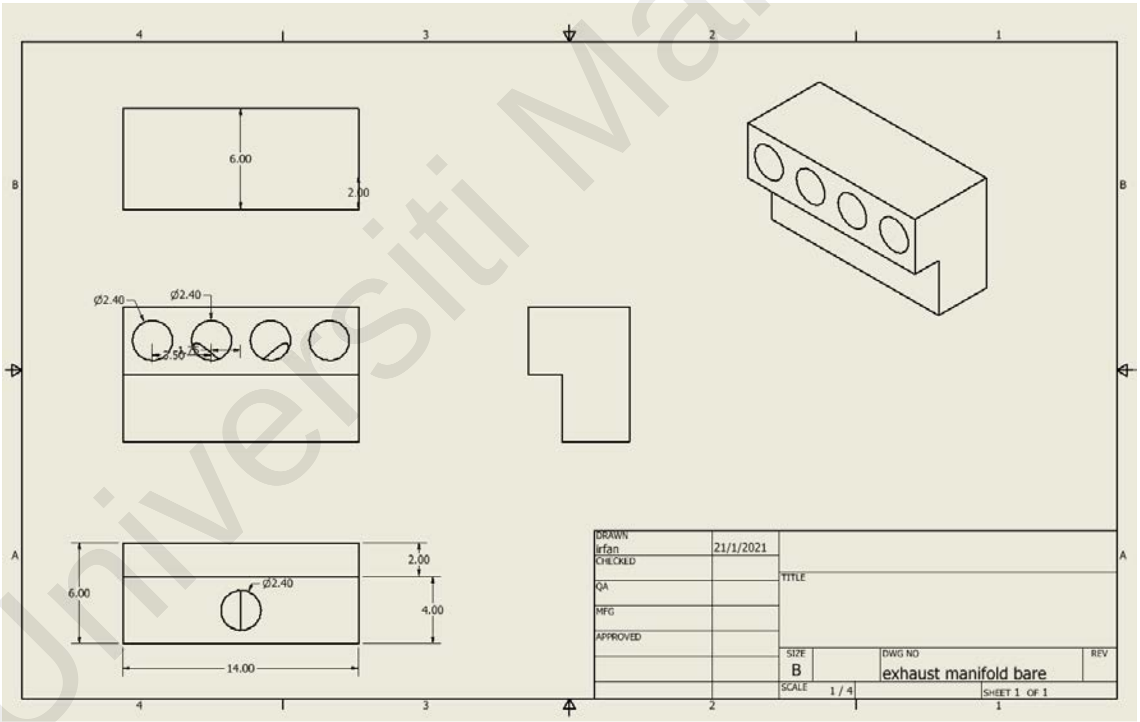

Figure 4.10: EM1 Drawing

Figure 4.11

The second model (EM2) was created to provide an example of coolant passages and inlet for the EGR valve. Since this is an iteration of the previous design, the bottom was shortened to emphasize the need to minimize the use of materials.

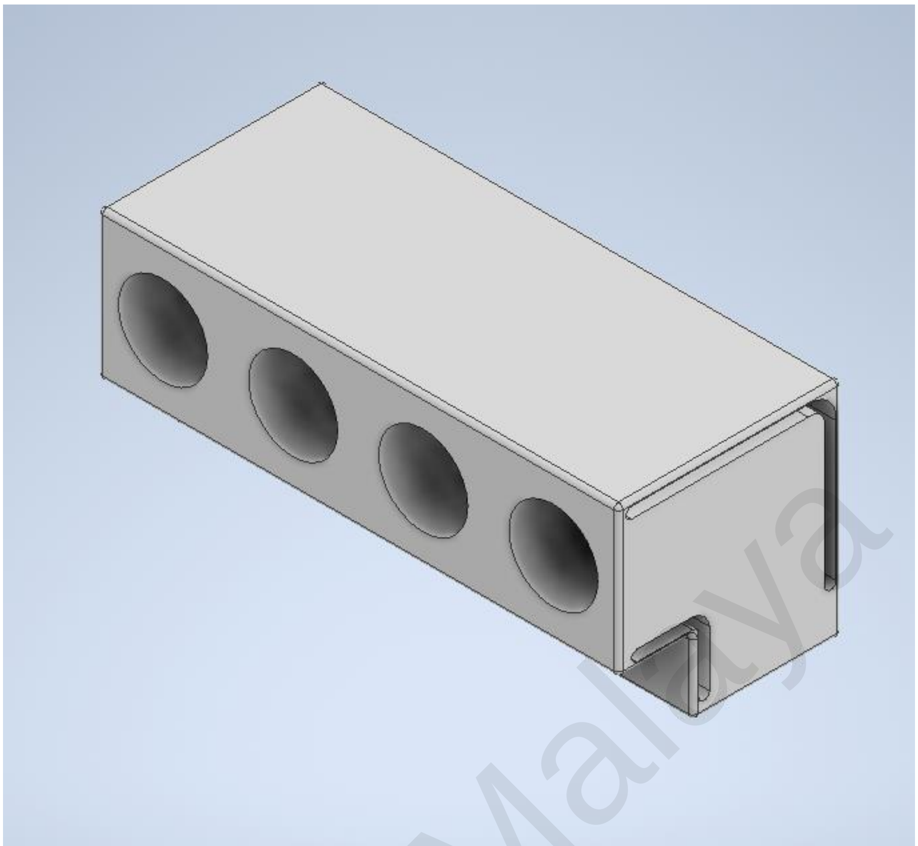

Figure 4.12: EM2 Main View

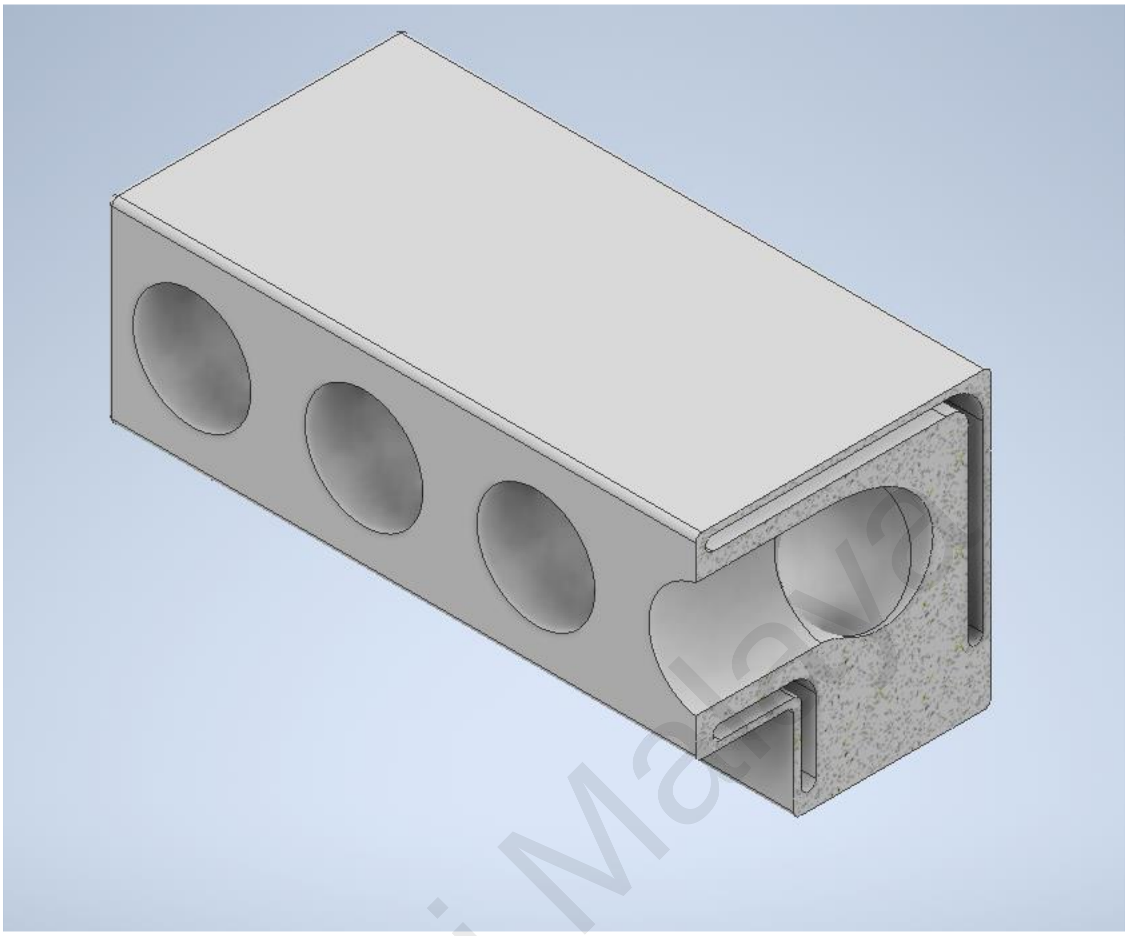

Figure 4.13: EM2 Cross Section 1

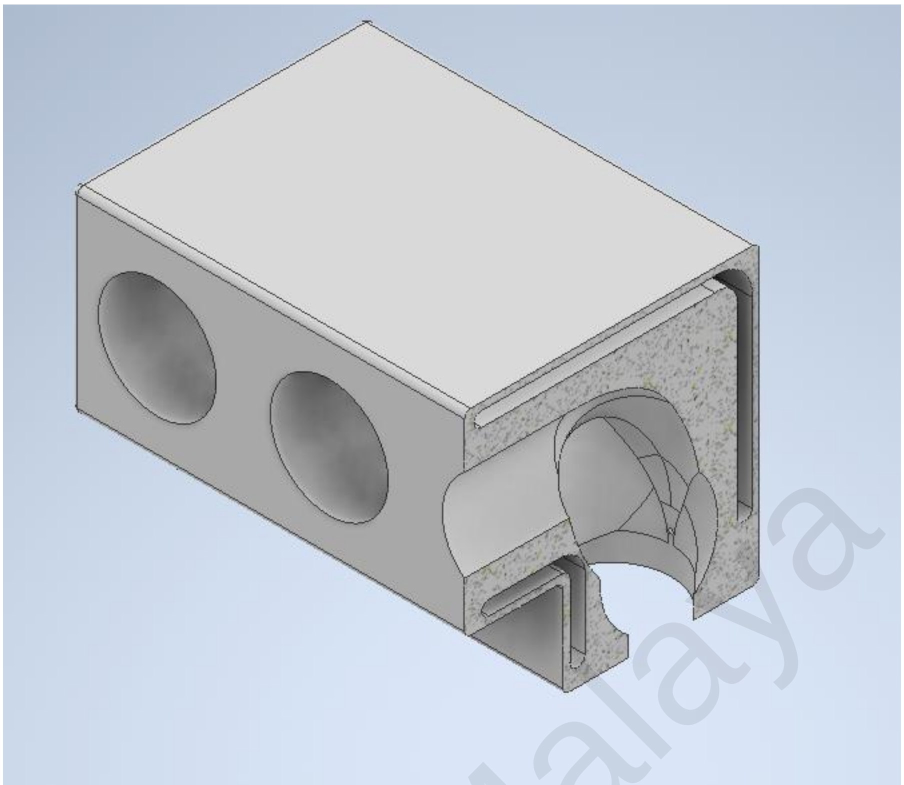

Figure 4.14: EM2 Cross Section 2

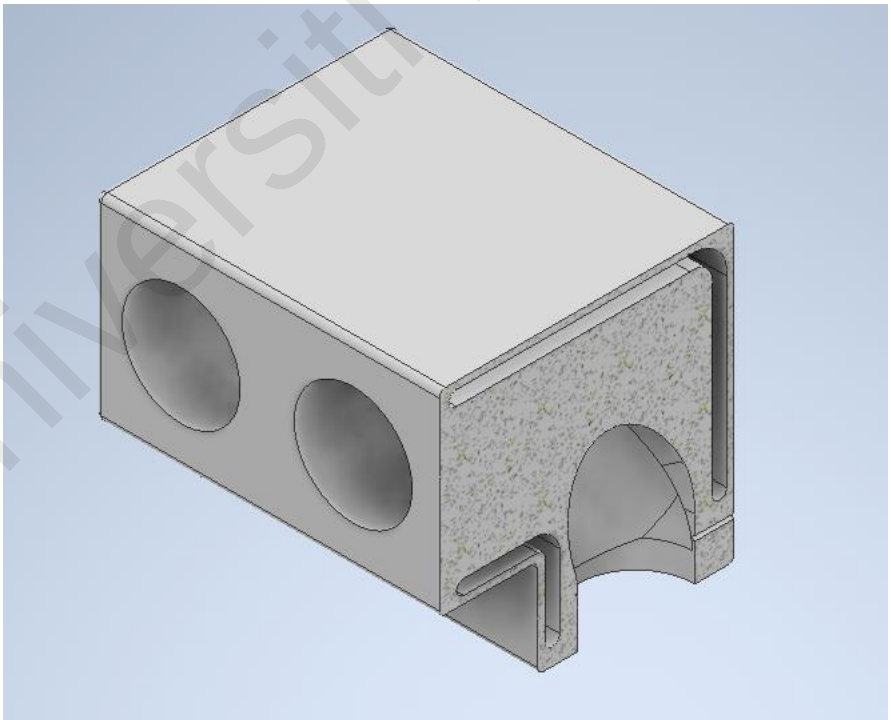

Figure 4.15: EM2 Half Section

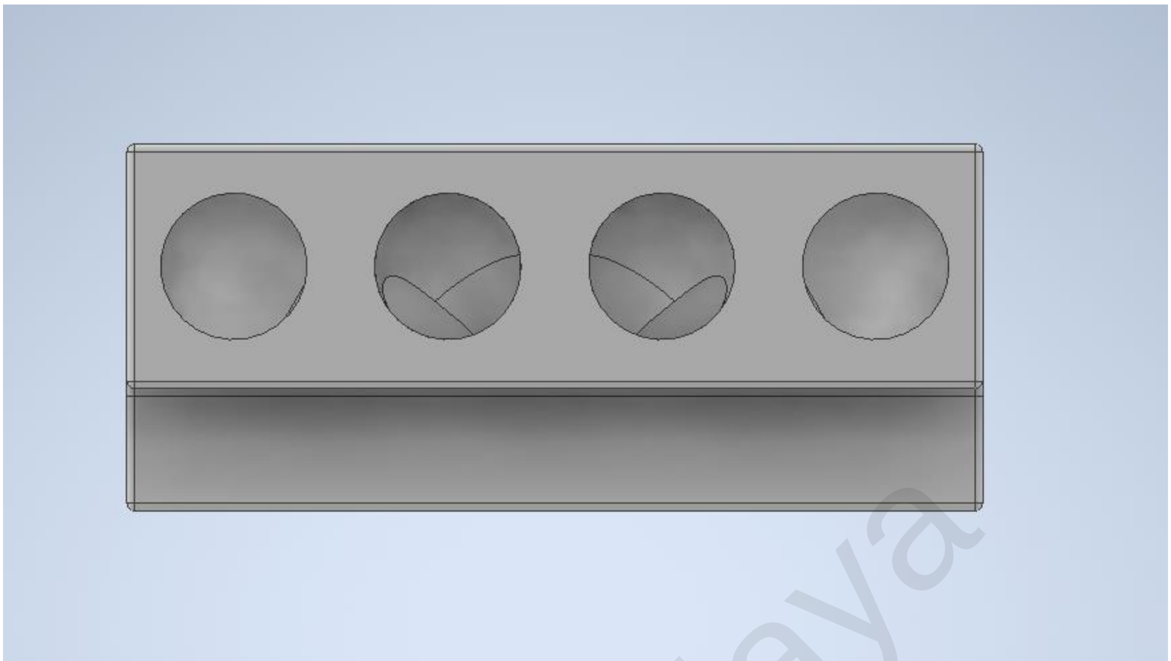

Figure 4.16: EM2 Front View

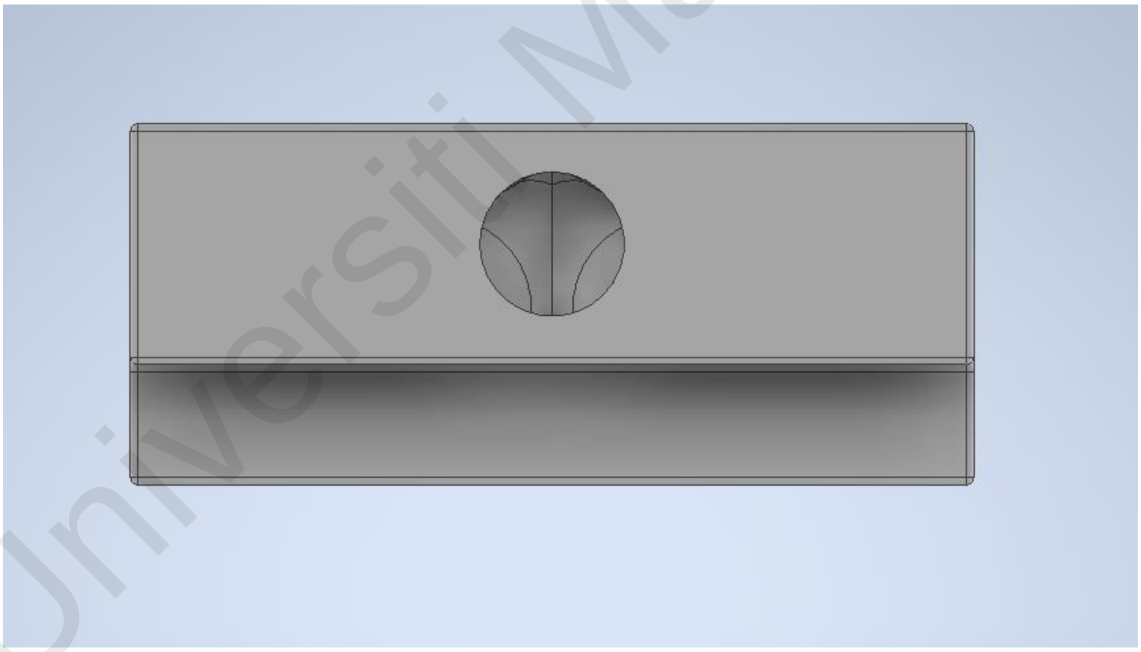

Figure 4.17: EM2 Bottom View

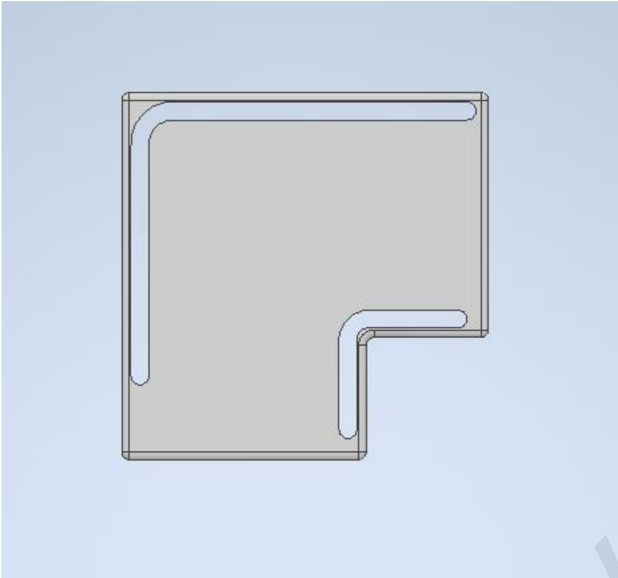

Figure 4.18: EM2 Side View

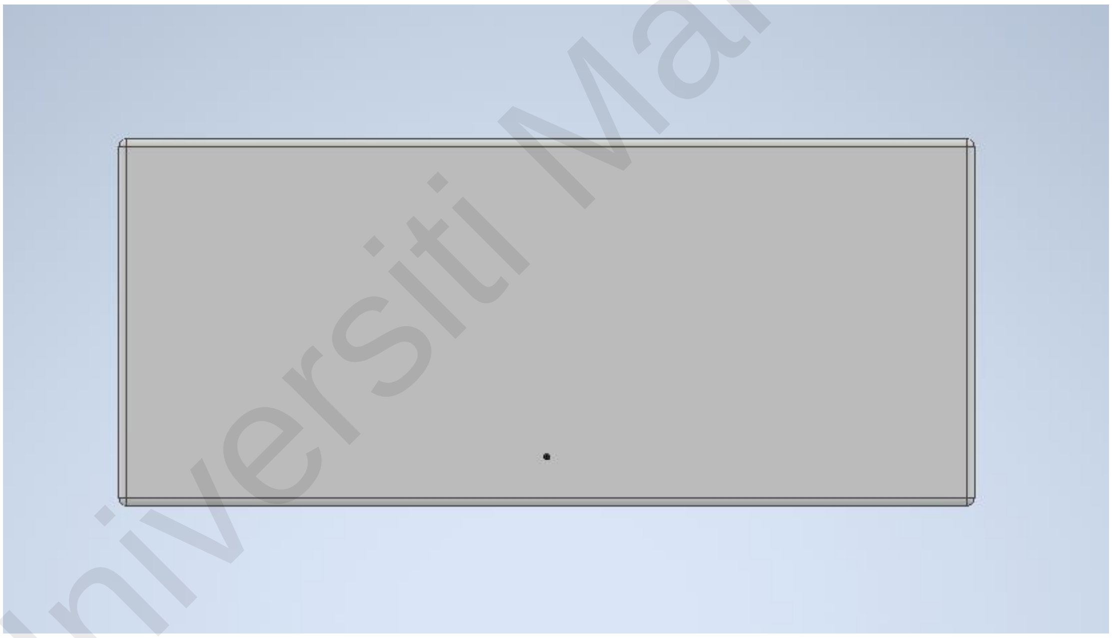

Figure 4.19: EM2 Back View

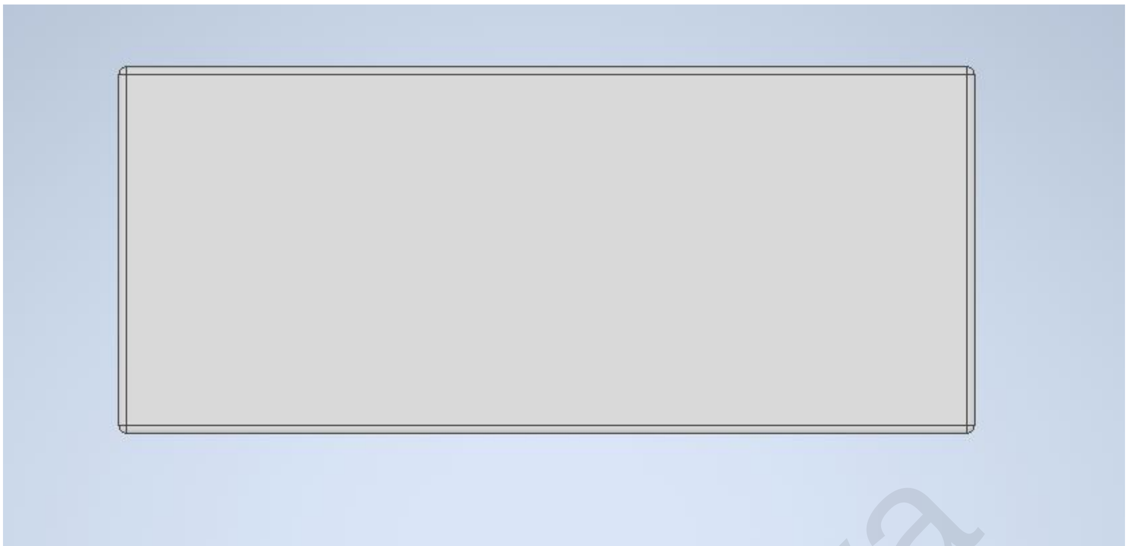

Figure 4.20: EM2 Top View

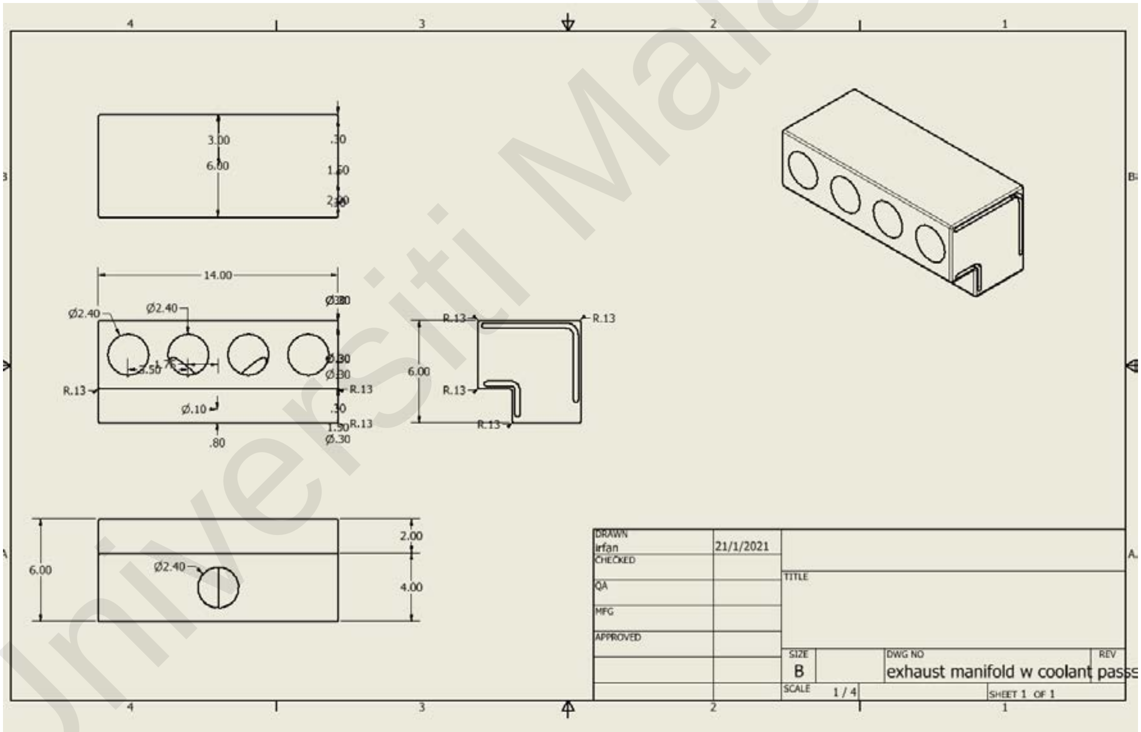

Figure 4.21: EM2 Drawing

The third model (EM3) m was created to provide a practical example of coolant passages and inlet for the EGR valve.

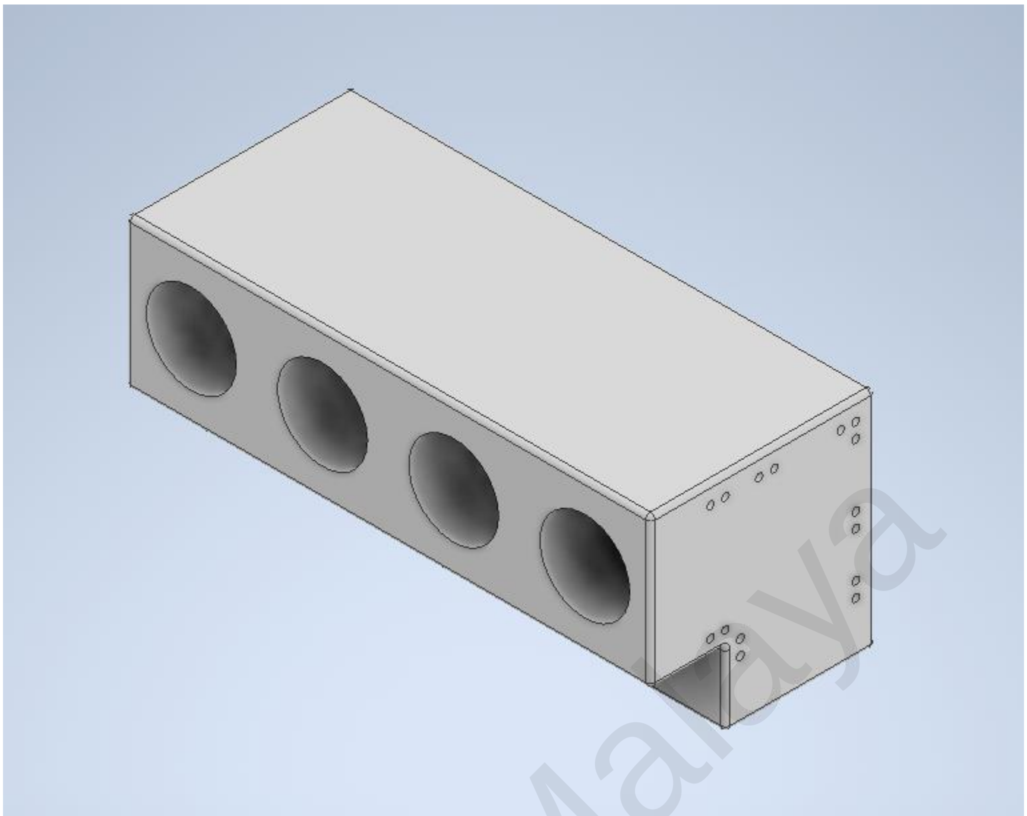

Figure 4.22: EM3 Main View

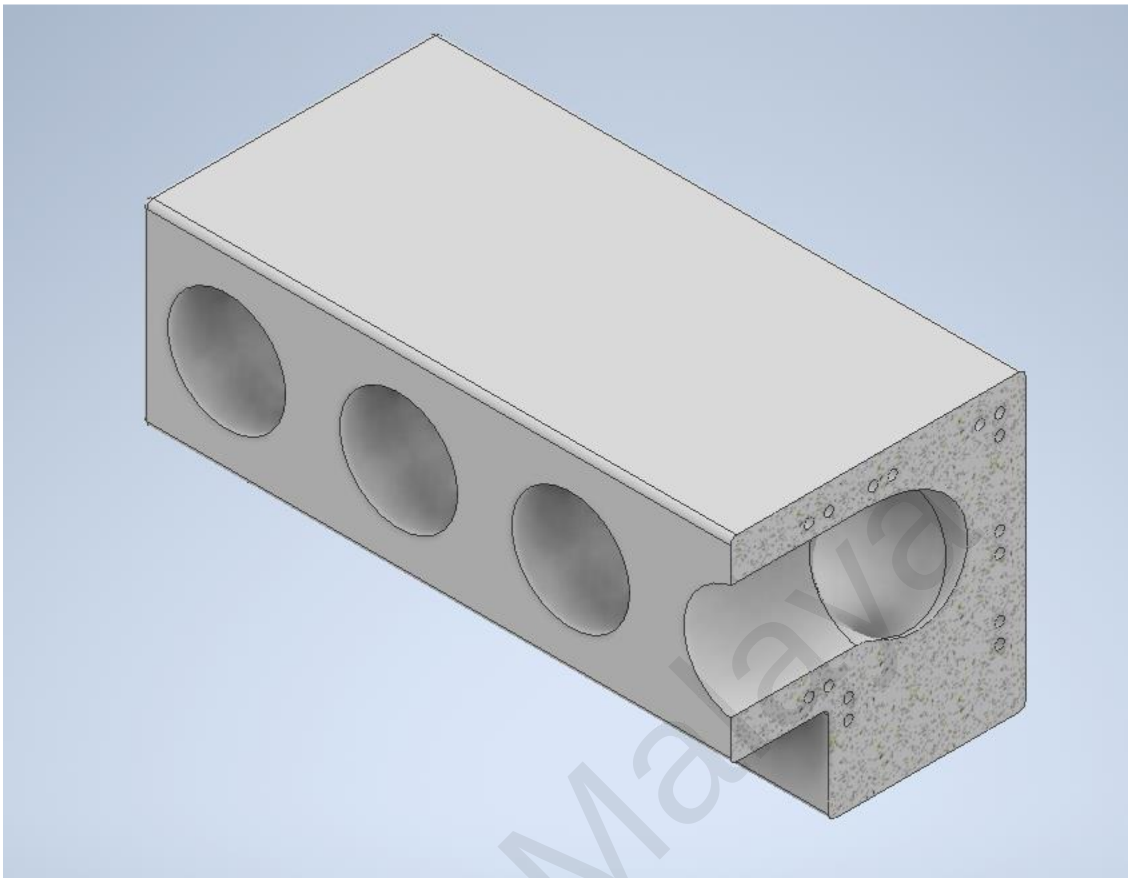

Figure 4.23: EM3 Cross Section 1

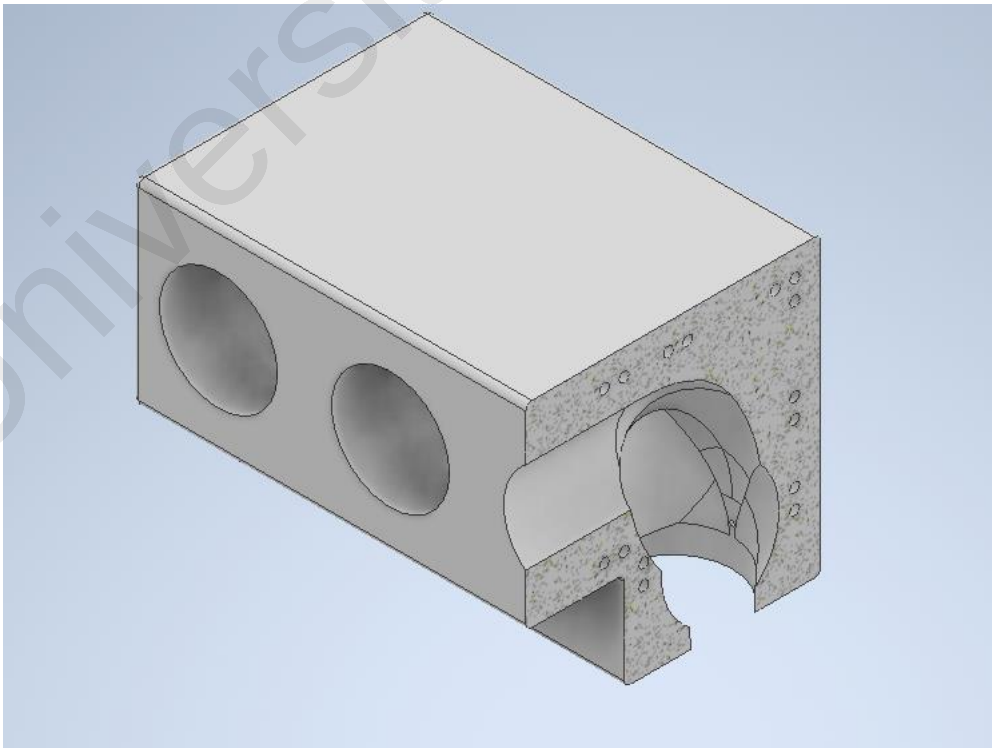

Figure 4.24: Cross Section 2

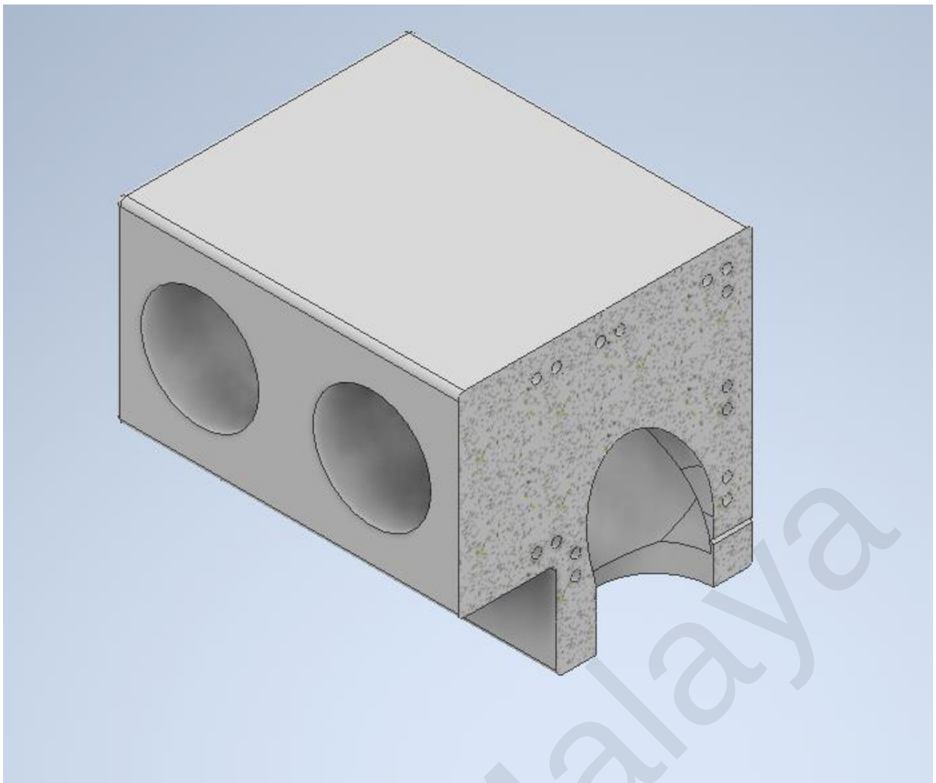

Figure 4.25: EM3 Half Section

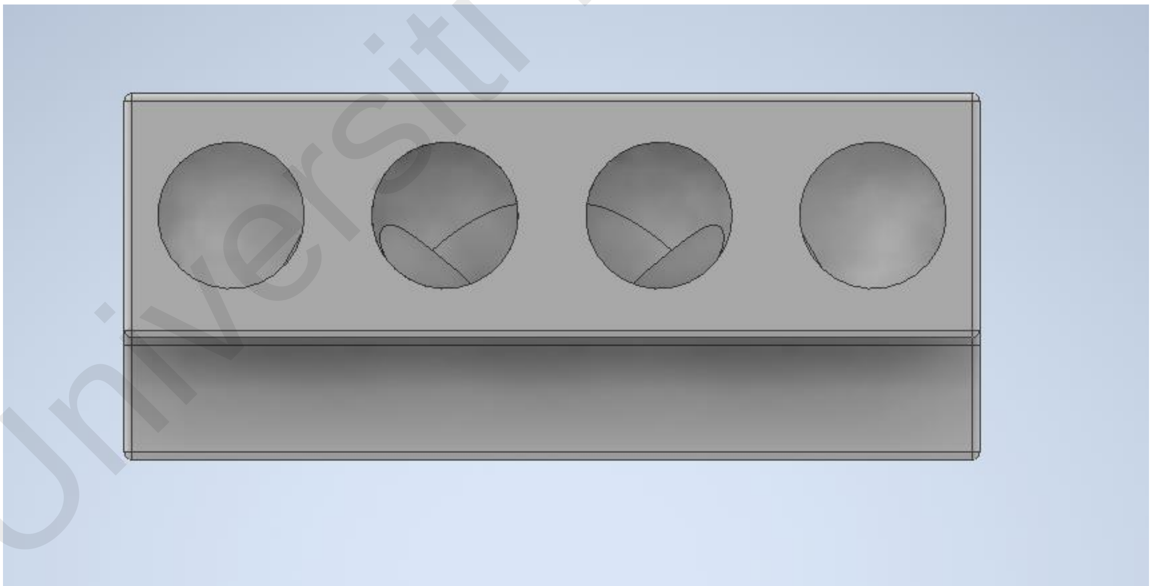

Figure 4.26: EM3 Front View

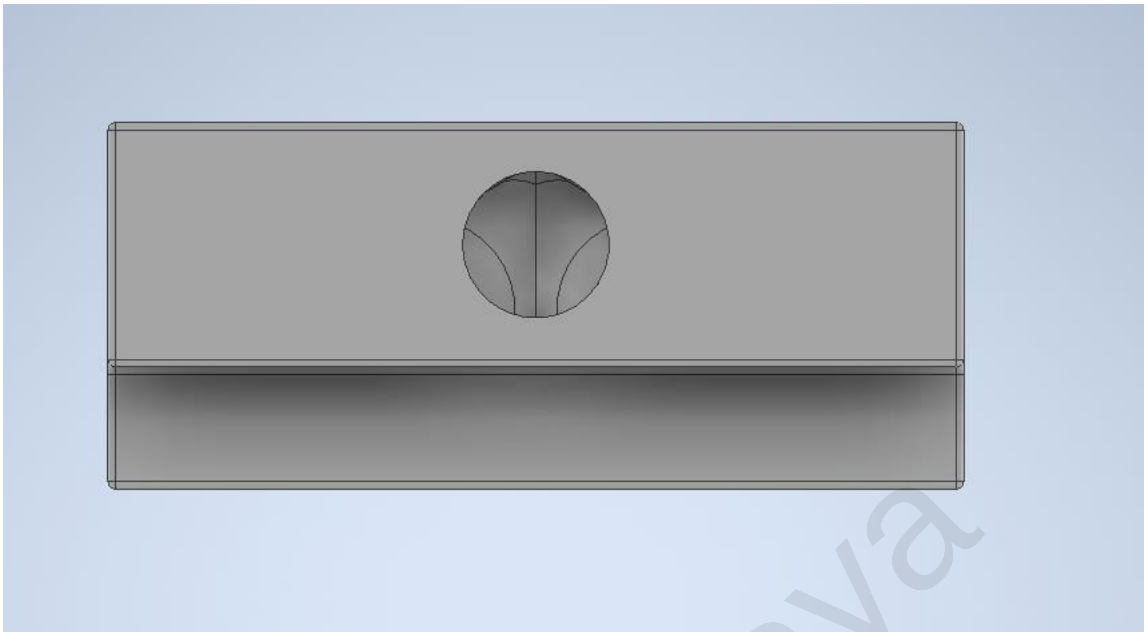

Figure 4.27: EM3 Bottom View

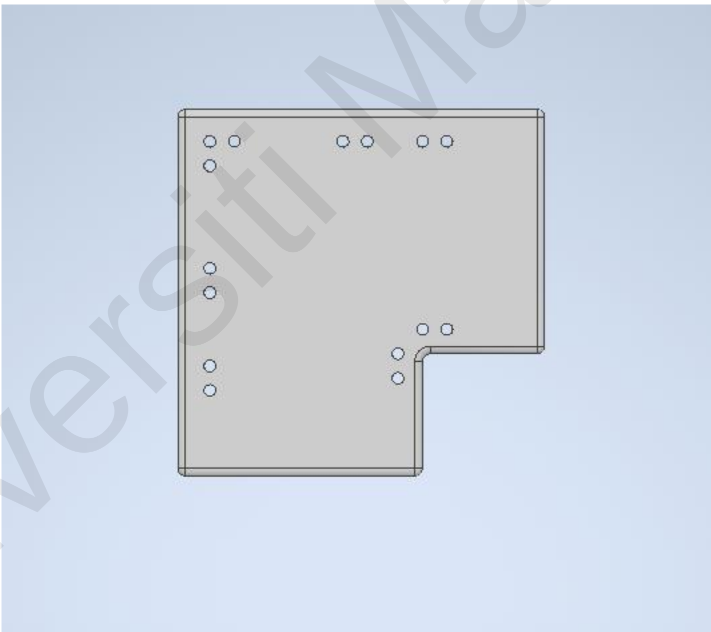

Figure 4.28: EM3 Side View

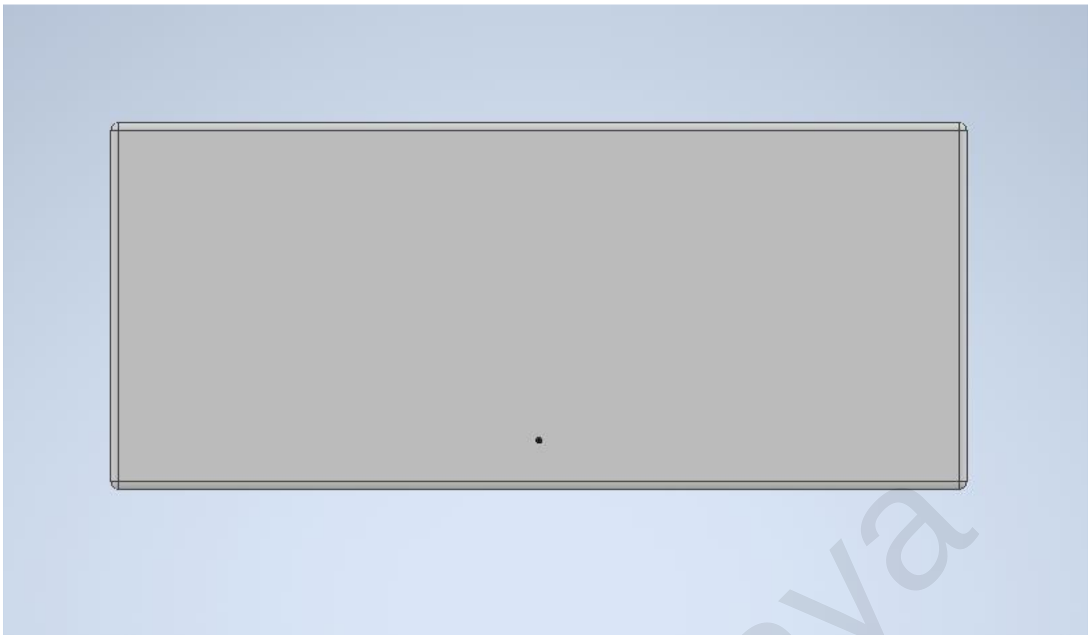

Figure 4.29: EM3 Back View

Figure 4.30: EM3 Top View

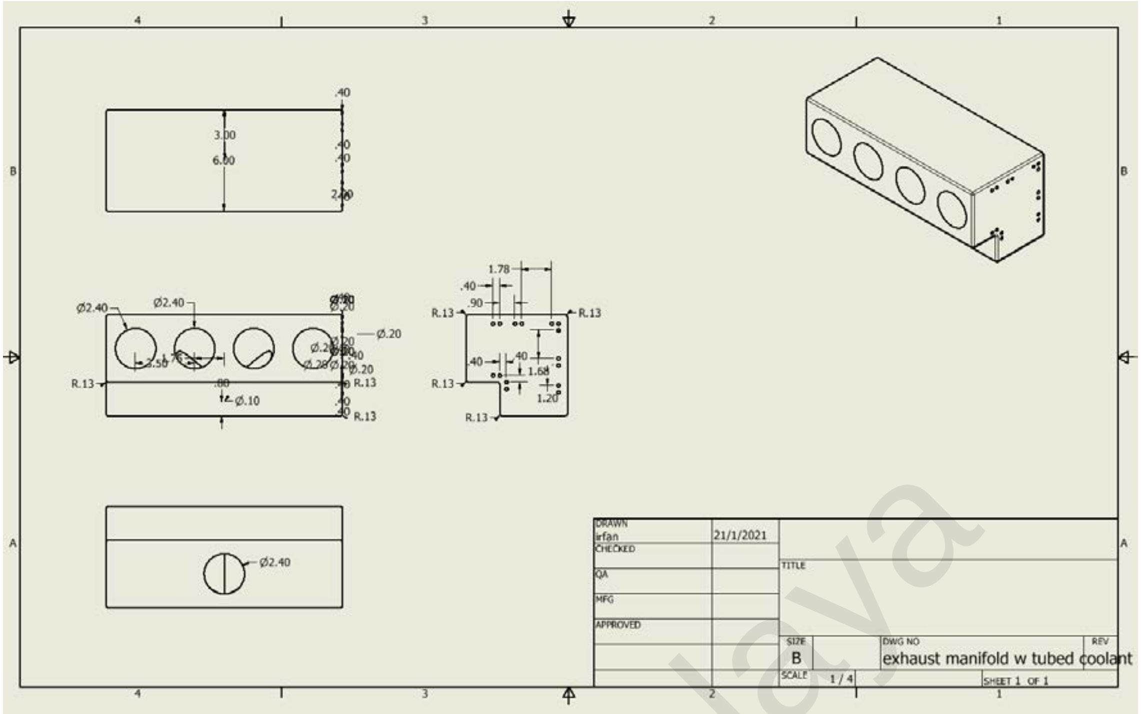

Figure 4.31: EM3 Drawing

The fourth model (EM4) was created to provide an example of various refinements to the outer body to improve heat exchange with fins.

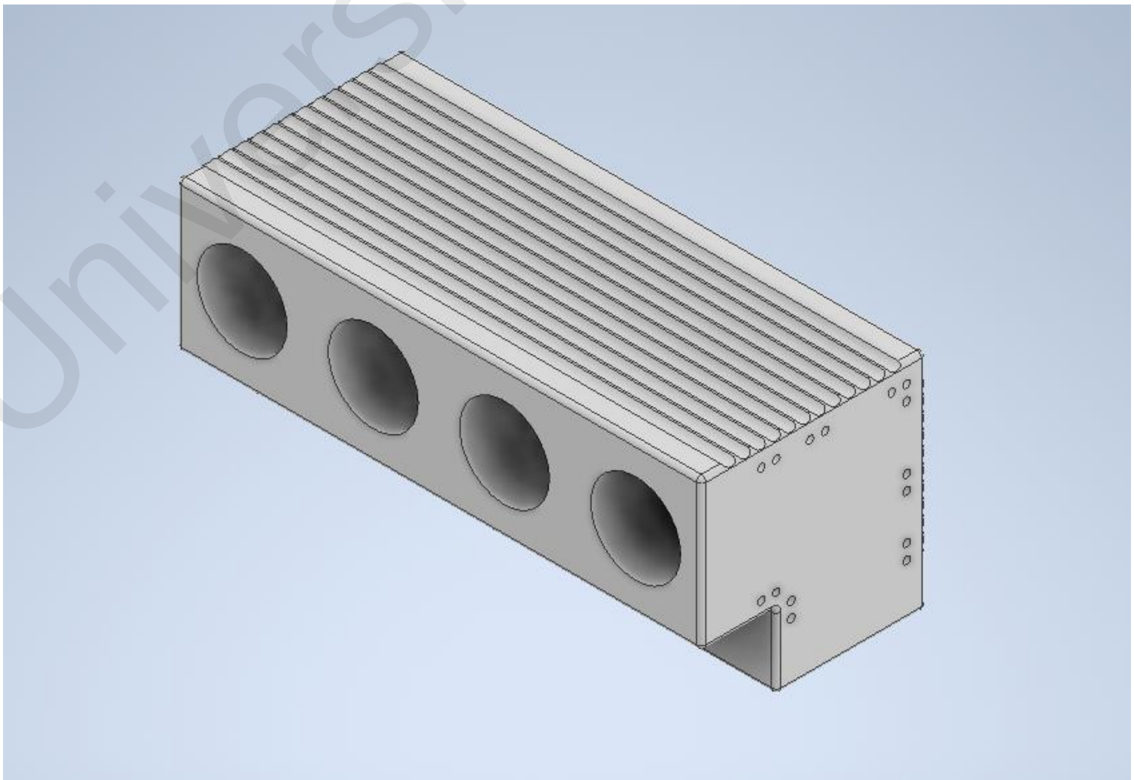

Figure 4.32: EM4 Main View

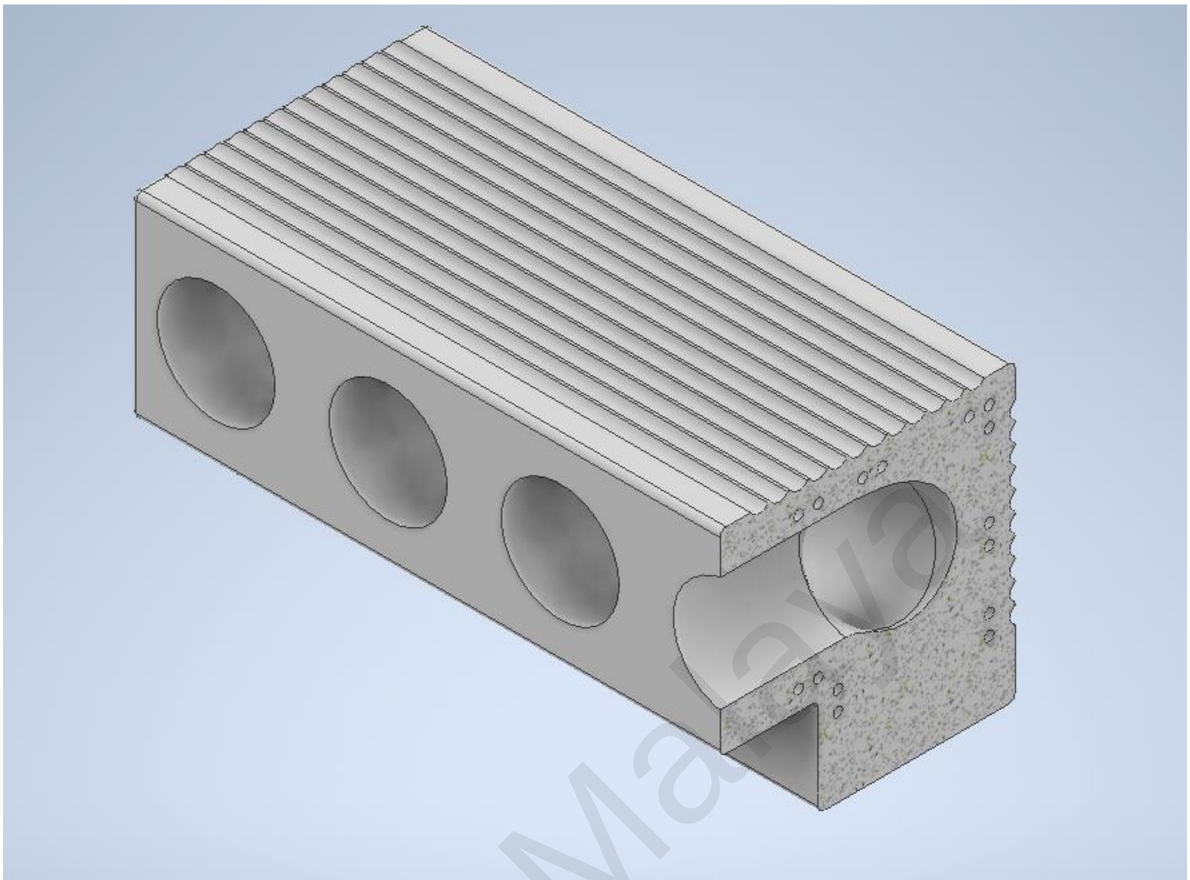

Figure 4.33: EM4 Cross Section 1

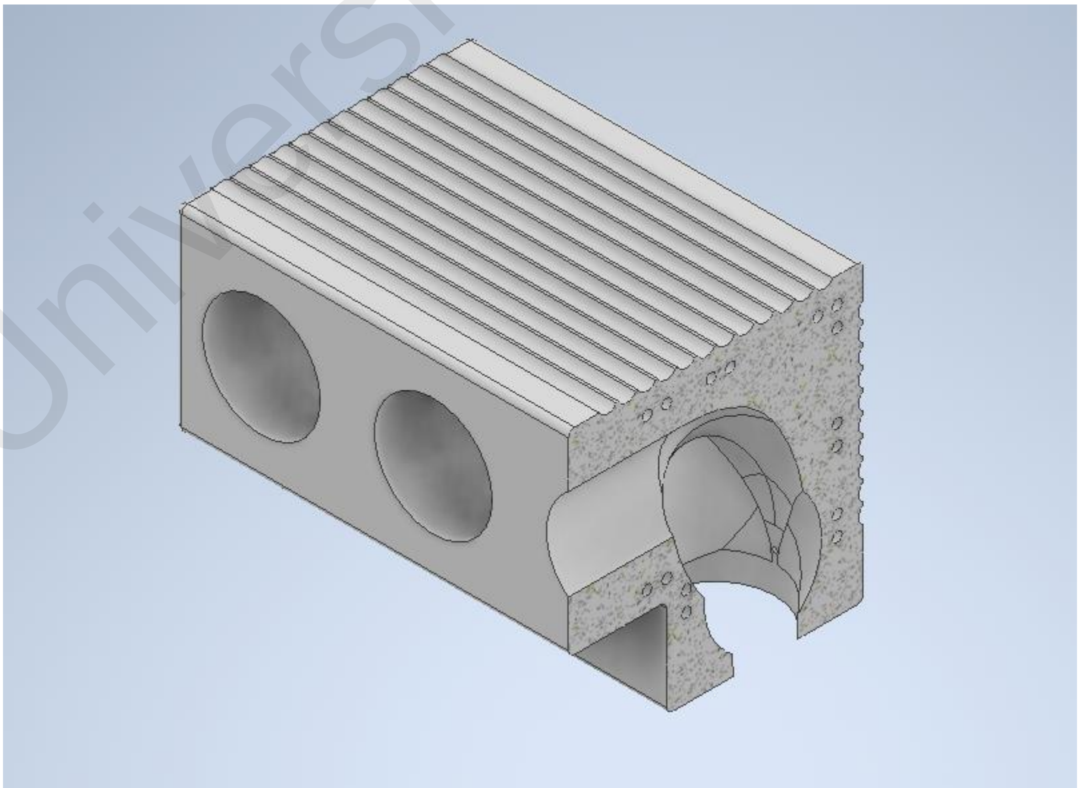

Figure 4.34: EM4 Cross Section 2

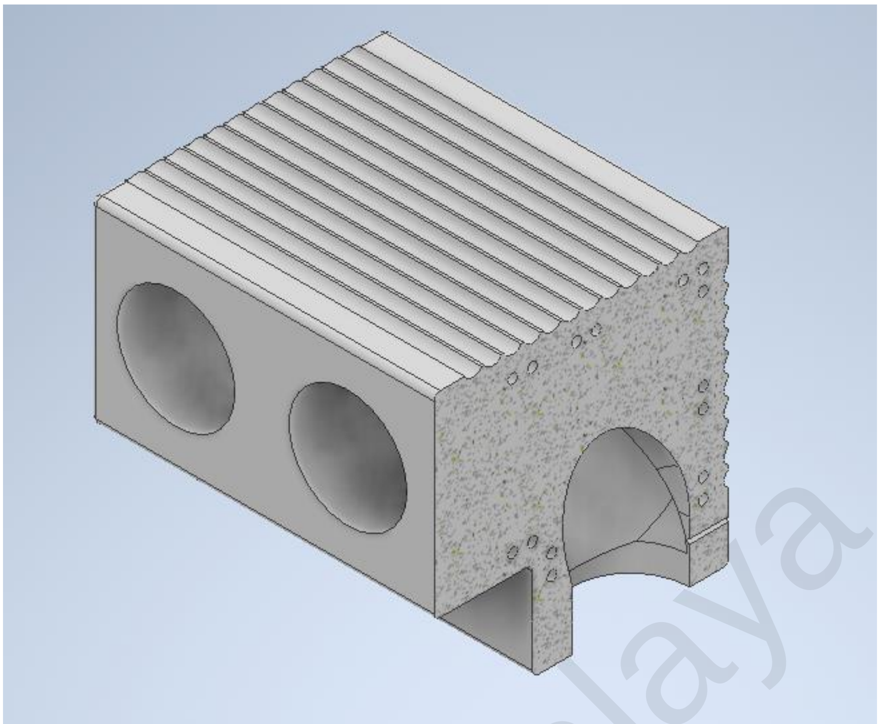

Figure 4.35: EM4 Half Section

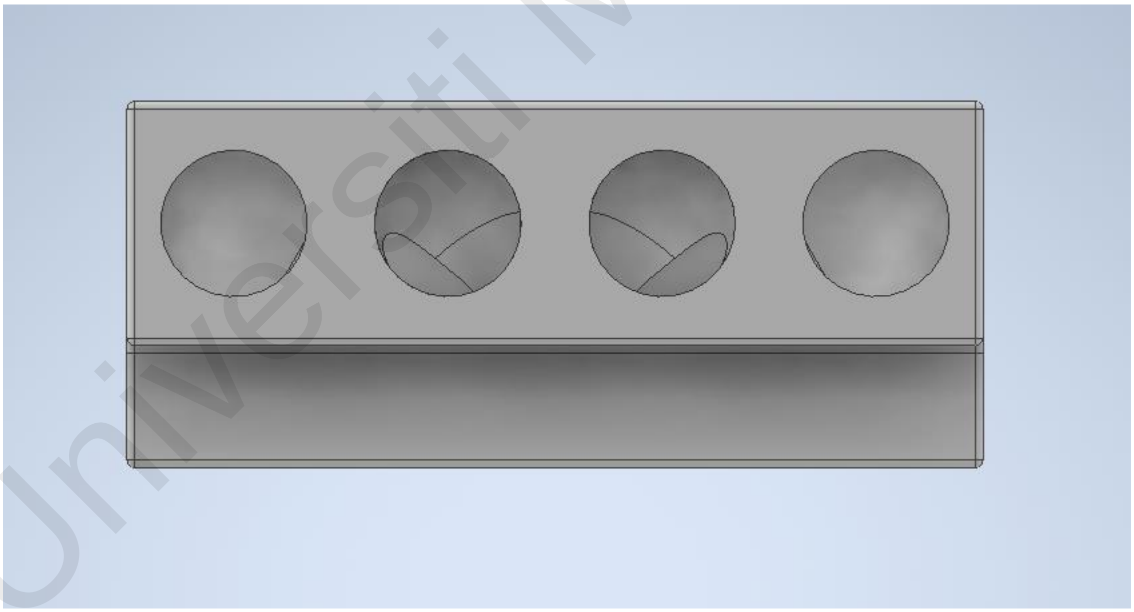

Figure 4.36: EM4 Front View

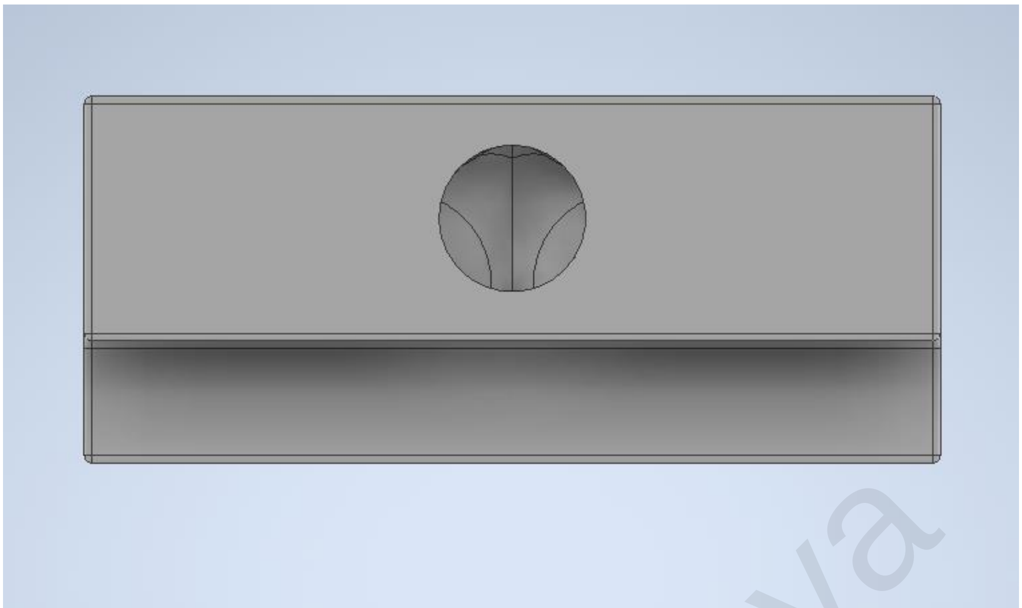

Figure 4.37: EM4 Bottom View

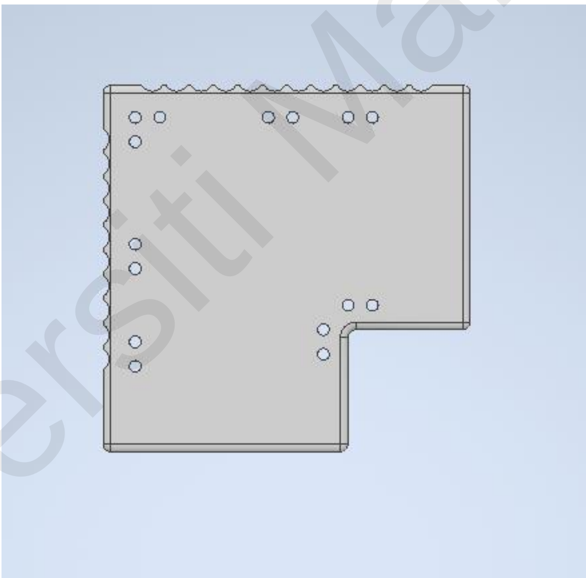

Figure 4.38: EM4 Side View

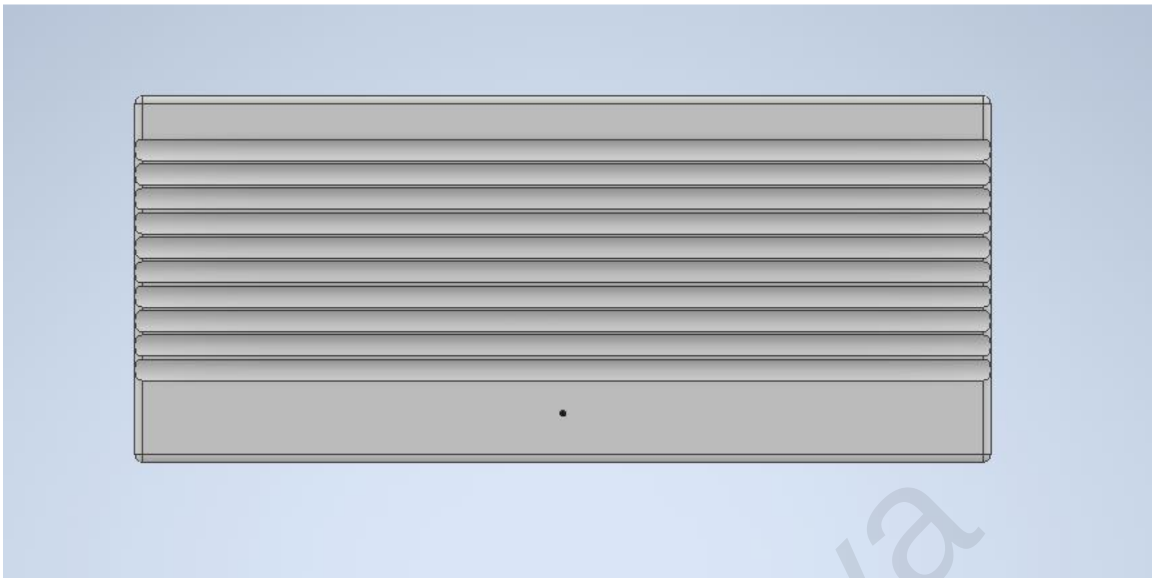

Figure 4.39: EM4 Back View

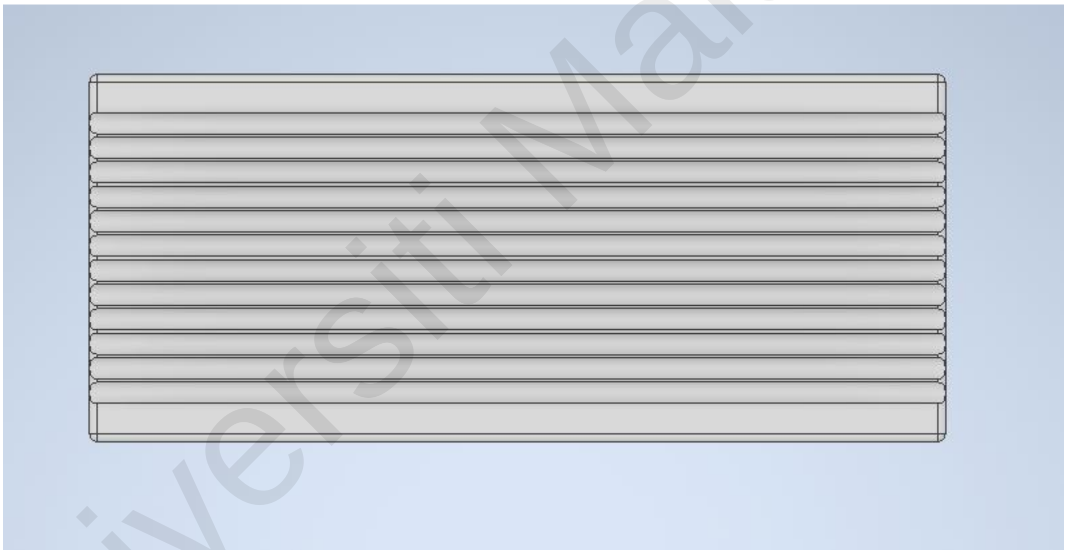

Figure 4.40: EM4 Top View

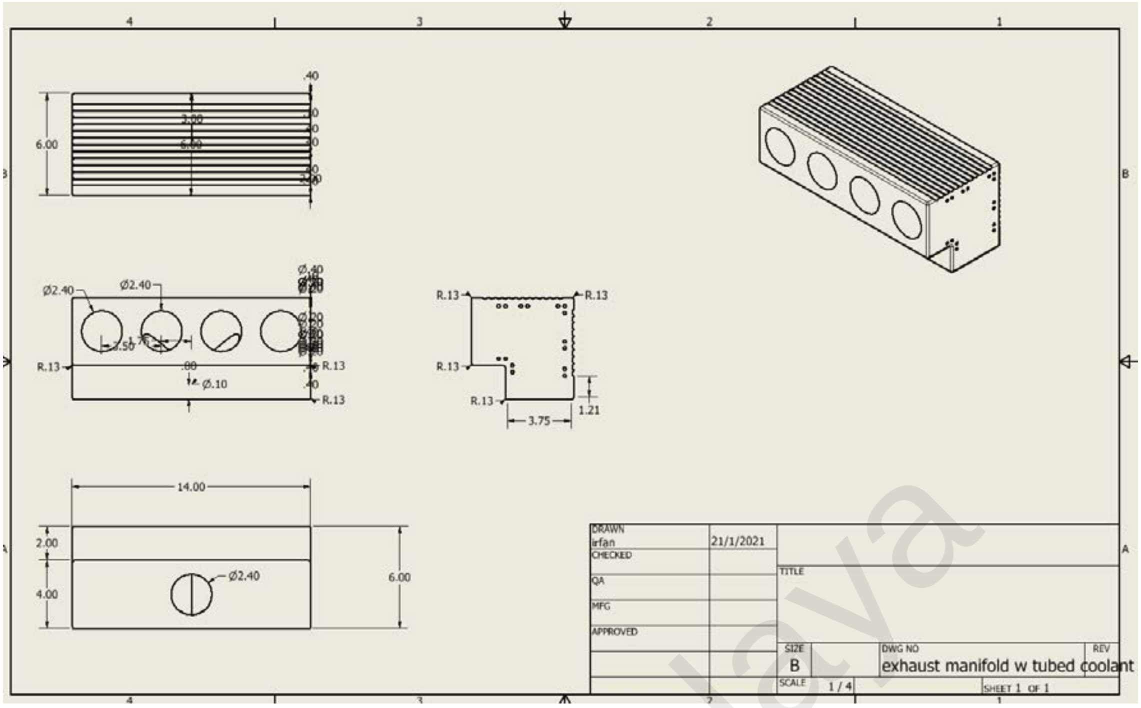

Figure 4.41: EM4 Drawing

The fifth model (EM5) was created to provide an example of various refinements to the outer body to improve heat exchange with fins and slots for lambda sensors.

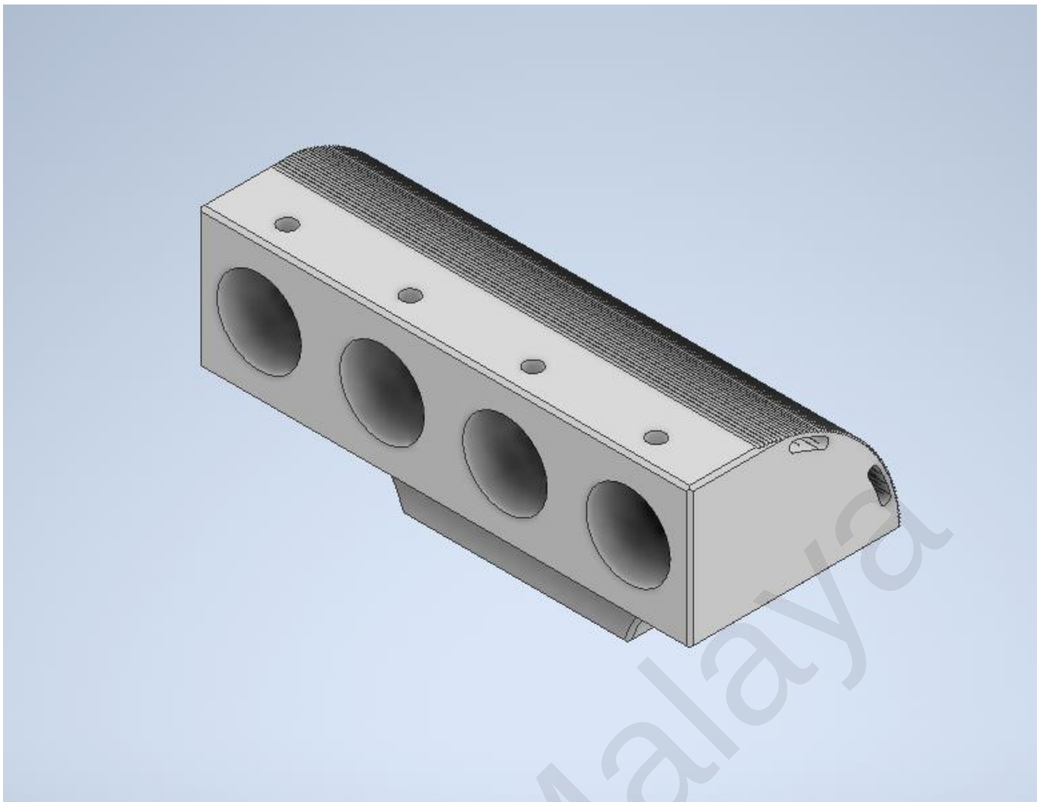

Figure 4.42: EM5 Main View

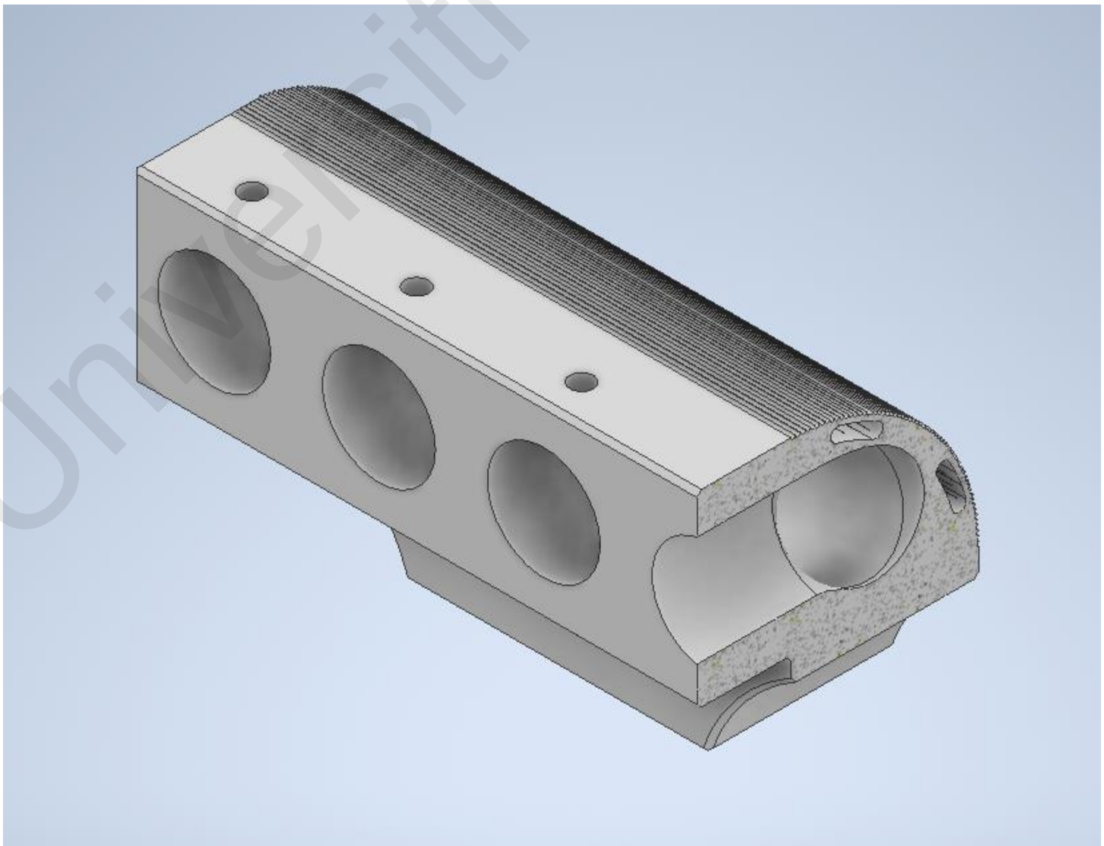

Figure 4.43: EM5 Cross Section 1

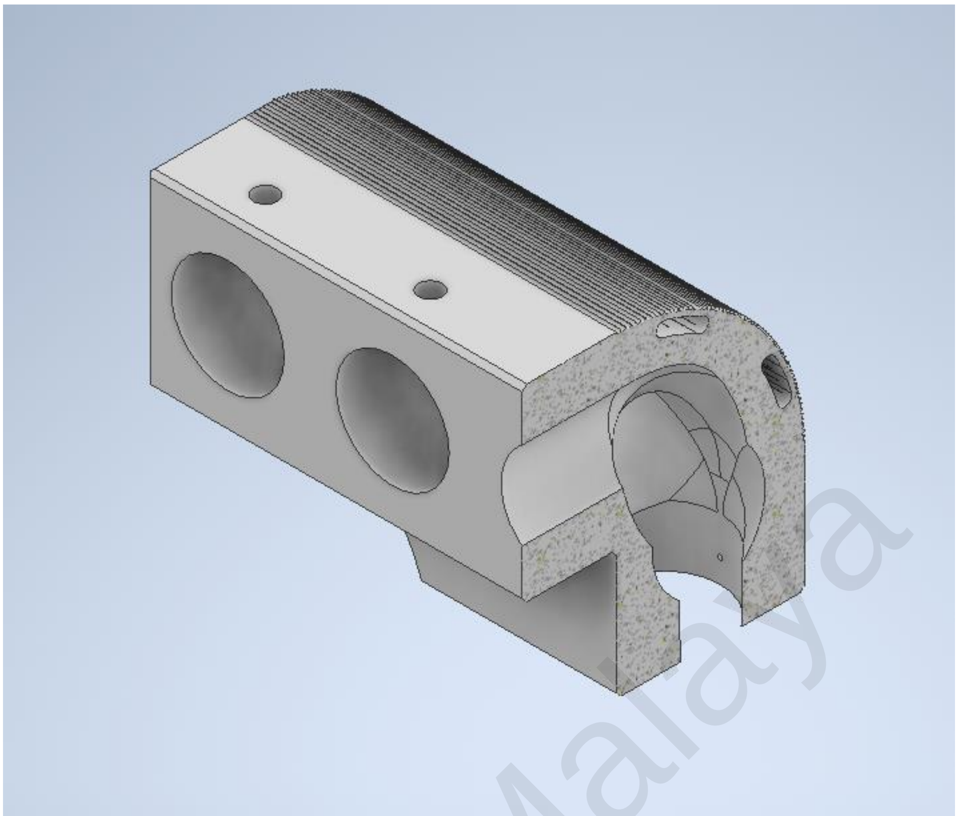

Figure 4.44: EM5 Cross Section 2

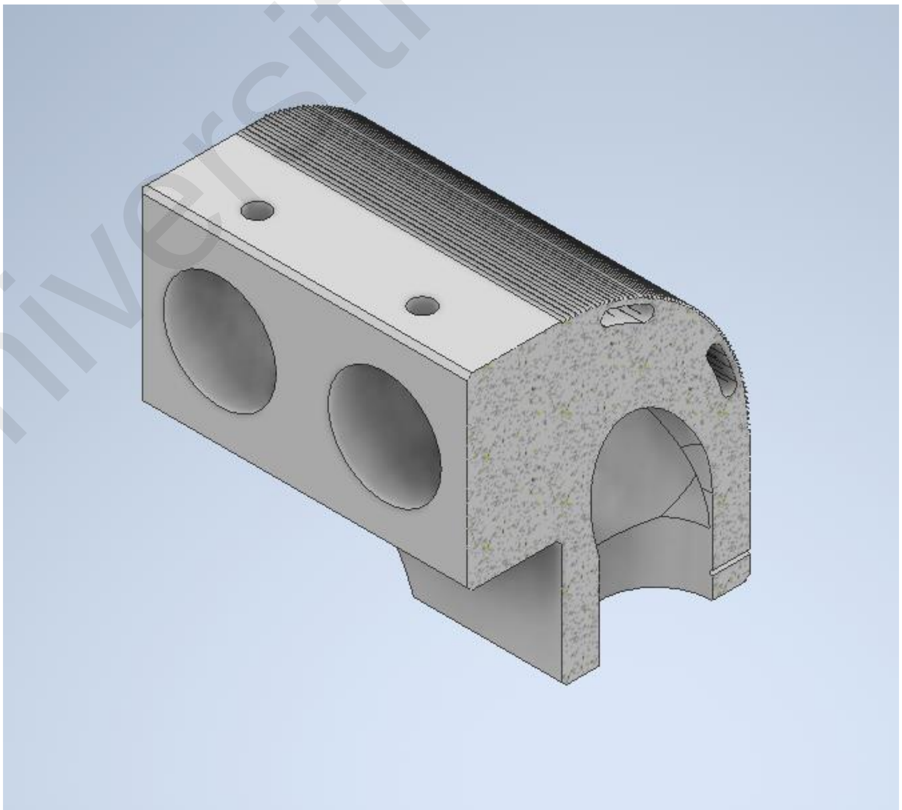

Figure 4.45: EM5 Half Section

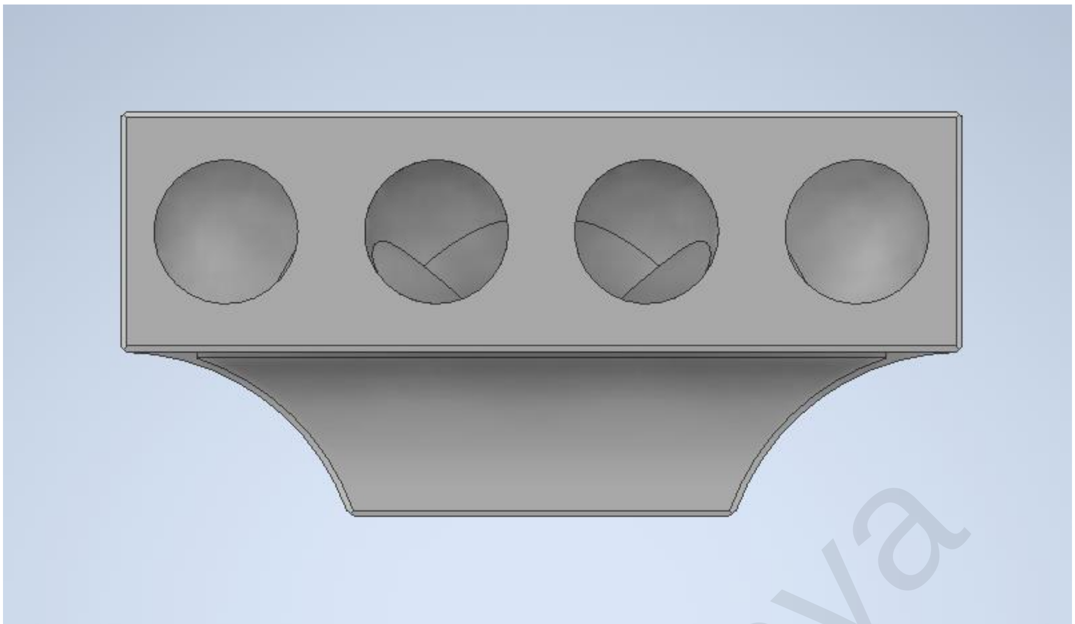

Figure 4.46: EM5 Front View

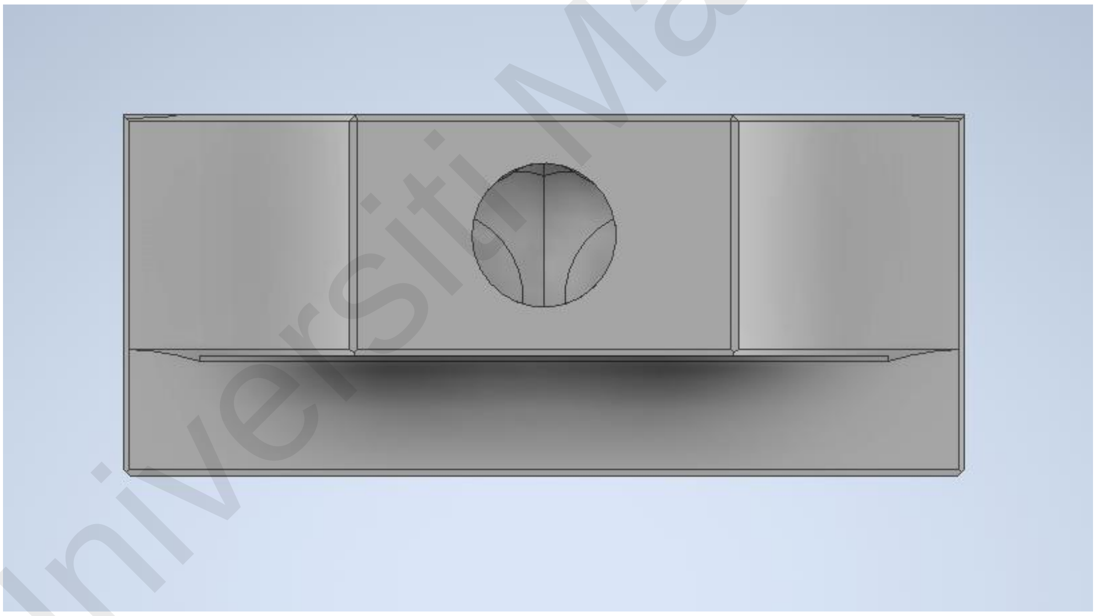

Figure 4.47: EM5 Bottom View

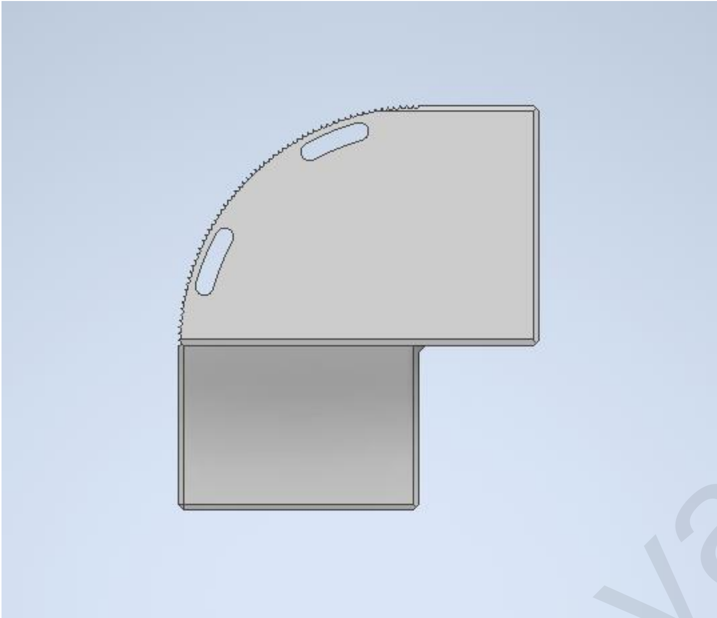

Figure 4.48: EM5 Side View

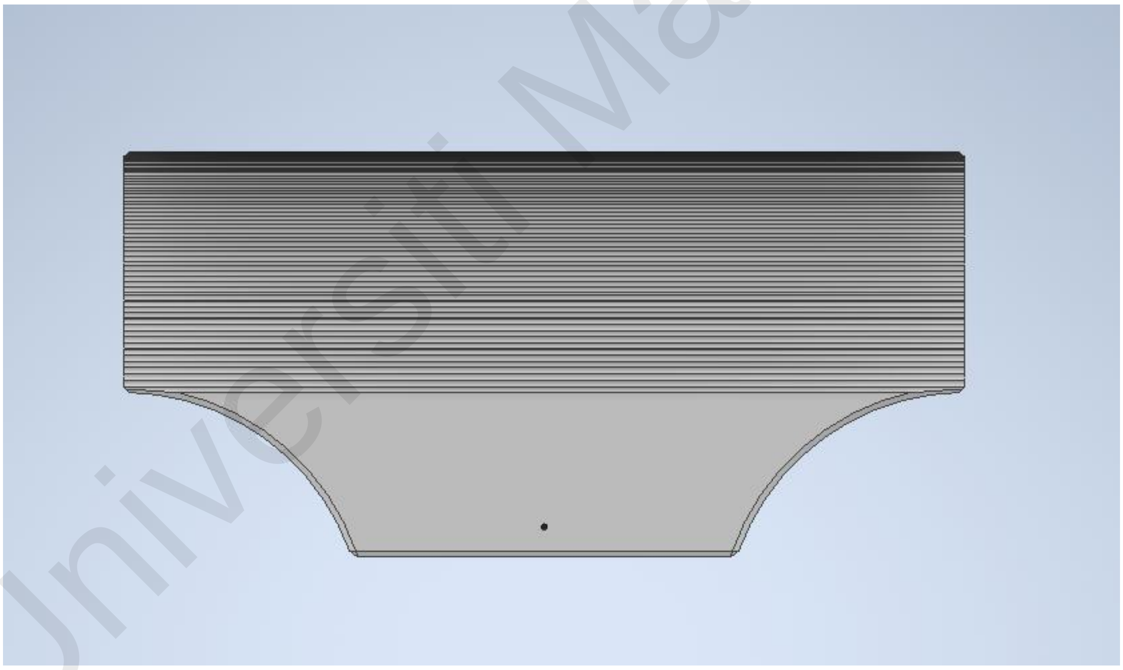

Figure 4.49: EM5 Back View

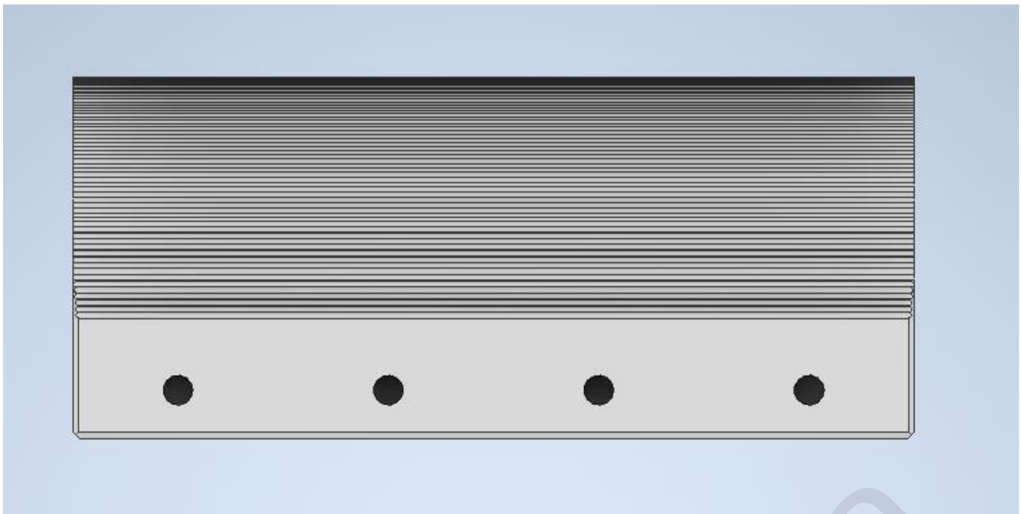

Figure 4.50: EM5 Top View

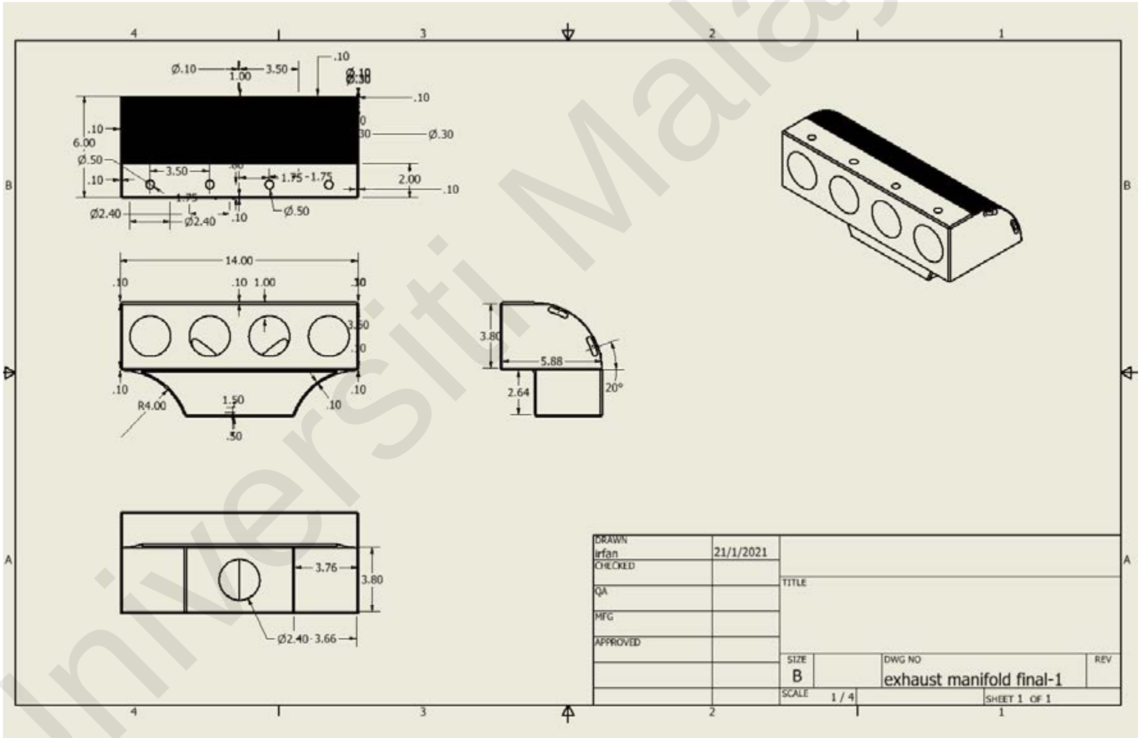

Figure 4.51: EM5 Drawing

4.2.3 Design Limitations

4.2.3.1 Material Used & Ease of Manufacturing

The preferable material to be used is aluminum due to its low thermal resistance and lightweight. However, it is generally more expensive to cast aluminum than it is to cast iron. Due to iron having a higher thermal resistance and is heavier in weight, further optimization on the design of the manifold has to take place.

Minimizing weight should also be a priority to minimize sagging of the manifold when installed onto the engine. The sagging will then unevenly wear out the gasket and ultimately leak raw exhaust gases into the atmosphere.

4.2.3.2 Coolant Passage Design

Optimize coolant passage design to maximize heat transfer from exhaust gas to coolant while maintaining ease of manufacturing and structural integrity. This will depend on the engine's exhaust gas characteristics and the material used to produce the recreated water-cooled exhaust manifold.

4.2.3.3 Exhaust Flow Design

Optimize exhaust flow design to minimize back pressure and promote scavenging while maintaining ease of manufacturing and structural integrity. This will depend on the engine's exhaust gas characteristics.

4.2.3.4 Placement of EGR Valve

The placement of the inlet of the EGR valve should be placed at the coolest point of the manifold, which is generally the lowest point of the manifold. However, the orientation may depend on the orientation of the engine in the vehicle.

4.3 Application of Design

The applications of this recreated exhaust manifold should be applied to engines that do not have an integrated exhaust manifold cylinder head. This is because IEMCH already have coolant passages running along the exhaust runners.

4.3.1 Gasoline Engines

For the application of the cooled exhaust manifold on naturally aspirated gasoline engines, the main advantages are the faster start-up time, potential in catalytic converter downsizing, and potentially less thermal stress on sensors and valves connected to the cooled manifold. The exhaust outlet on the manifold should be attached directly to a catalytic converter to simplify the piping of the exhaust piping to reduce cost and complexity.

For the application of the cooled exhaust manifold on turbocharged gasoline engines, the main advantages are the same as of those of naturally aspirated as mentioned above, and additionally the lower thermal stress on the turbocharger. The turbocharger should be attached at the outlet of the cooled exhaust manifold to minimize piping complexity and costs. An additional inlet for an EGR valve could be added after the turbocharger to provide a Low Pressure EGR Loop for additional options for appropriate applications and loads.

4.3.2 Diesel Engines

The application of water-cooled exhaust manifolds have already existed on diesel engines; a further integration of lambda sensor ports would further reduce costs for retrofitting on cylinder heads without lambda sensors included in the block and an optimum EGR valve inlet position would further improve the reduction of the EGR temperature.

For naturally aspirated diesel engines, the catalytic converter should be attached directly to the outlet of the exhaust manifold to minimize piping complexity and cost.

For turbocharged diesel engines, the turbine housing of the turbocharger should be attached to the outlet of the exhaust manifold to minimize piping complexity and cost.

Also, another inlet for another EGR loop (Low Pressure Loop) after the turbine may be an additional option to provide various levels and pressures of EGR for the appropriate application and load. However, it is preferable for EGR to travel through a High-Pressure Loop to prevent exposure of exhaust gases to the compressor and intercooler.

4.3.3 Homogenous Charged Combustion Ignition Engines

A concept for this cooled exhaust manifold to applied to HCCI engines is to replace it as an exhaust manifold and have a thermostat attached to one of the coolant exit points to measure variations in temperatures. These variations in temperature can further tell us the condition of combustion instead of relying solely on the lambda sensors.

4.4 Future of Research

After addressing the design limitations, thermo-fluid analysis should take place to analyze heat transfer of the exhaust gases to the coolant. The next analysis should be on thermal fatigue of the exhaust manifold. After these analyses, there should be a redesign of the exhaust manifold. A physical prototype should be made and be fitted onto an existing engine for real world testing.

4.5 Current Project Limitations

During this project, there have been several limitations into gathering data and furthering research. This is due to the restriction of inter-district and interstate travel because of the COVID-19 outbreak which has limit students and staff to access university facilities. One of the initial plans was to simulate the exhaust gas flow and coolant flow for thermo-fluid analysis. However, existing hardware limited the usage of ANSYS Fluent to 2D analysis. Also, more complex designs could be rendered if not due to the limited existing hardware available.

CHAPTER 5: CONCLUSION

To conclude this research paper, the technologies of IEMCH, EGR and water-cooled exhaust manifold have been analyzed. The basic concepts of each technology were considered and were used to create a redesigned water-cooled exhaust manifold. While the use of water-cooled exhaust manifolds for the purpose of reducing temperature of EGR, it has only been used in propulsion applications to reduce NOx.

For the research project's objectives, analysis on literature review on the technology applied in modern engines to reduce emissions (IEM, EGR and Water-Cooled Exhaust Manifold) and highlight important concepts to extract to recreate a water-cooled exhaust manifold was successful. 3-D Modelling to recreate a water-cooled exhaust manifold which incorporates the concepts from the previously mentioned technologies and provide rendered models of various water-cooled exhaust manifold designs was successful. However, analysis on structural integrity and heat transfer flux between fluids in the recreated water-cooled exhaust manifold to ensure the designs are able to perform and extract heat successfully was not successful due to hardware limitations and restriction.

The redesigned water-cooled exhaust manifold is planned to be applied in the automotive industry to be retrofitted onto existing engines. Therefore, the options to reduce emissions must be focused on how easily a system can be implemented onto older designs and structures.

The redesigned water-cooled exhaust manifold hopes to reduce exhaust gas temperatures for EGR purposes. This in turn helps to reduce heat being rejected into the surrounding by having the coolant extract heat away from the exhaust gas. Also, this improves warm up times from cold starts due to the heat from the exhaust gas simultaneously is transferred to the coolant which also shares the same reservoir as the coolant used in the main engine block. Furthermore, the reduction in temperature gas can potentially downsize the catalytic converter due to less heat being needed to reach optimal temperature. This leads to a reduction in manufacturing costs.

Several design and concepts have been shown to help visualize the redesigned water-cooled exhaust manifold. Different designs were used to highlight different aspects that may fit a certain engine's orientation or space requirement.

While several designs have been shared, all of them could not be tested due to hardware limitations, software limitations, and COVID-19 with the inter-district and inter-state travels restricted.

REFERENCES

Abd-Alla, G. H. (2002). Using exhaust gas recirculation in internal combustion engines: a review. Energy Conversion and Management, 43(8), 1027-1042.

Agarwal, D., Singh, S. K., & Agarwal, A. K. (2011). Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine. Applied energy, 88(8), 2900-2907.

Amann, M., Alger, T., & Mehta, D. (2011). The effect of EGR on low-speed pre-ignition in boosted SI engines. SAE International Journal of Engines, 4(1), 235-245.

Beychok, M. R. (1973). NOX emission from fuel combustion controlled. Oil Gas J, 71(9), 53-56.

Bozza, F., De Bellis, V., & Teodosio, L. (2016). Potentials of cooled EGR and water injection for knock resistance and fuel consumption improvements of gasoline engines. Applied Energy, 169, 112-125.

Chen, M., Wang, Y., Wu, W., Cui, Q., Wang, K., & Wang, L. (2016). Thermal-Mechanical Fatigue Prediction of Aluminum Cylinder Head with Integrated Exhaust Manifold of a Turbo Charged Gasoline Engine (No. 2016-01-1085). SAE Technical Paper.

Dymarski, C., & Narewski, M. (2016). Simplified method of water cooled exhaust system design and performance assessment. Journal of Polish CIMEEAC, 11(1), 23-29.

Feng, D., Wei, H., & Pan, M. (2018). Comparative study on combined effects of cooled EGR with intake boosting and variable compression ratios on combustion and emissions improvement in a SI engine. Applied Thermal Engineering, 131, 192-200.

Grandin, B., Ångström, H. E., Stålhammar, P., & Olofsson, E. (1998). Knock suppression in a turbocharged SI engine by using cooled EGR (No. 982476). SAE Technical Paper.

Grondin, O., Moulin, P., & Chauvin, J. (2009, December). Control of a turbocharged diesel engine fitted with high pressure and low pressure exhaust gas recirculation systems. In Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 2009 28th Chinese Control Conference (pp. 6582-6589). IEEE.

He, G., Wang, X. C., & Shi, X. Y. (2012). Cooling performance of diesel exhaust water-collecting box and its influencing factors. Journal of Naval University of Engineering, 24(1), 64-67.

Hoen, K. M. R., Tan, T., Fransoo, J. C., & Van Houtum, G. J. (2014). Effect of carbon emission regulations on transport mode selection under stochastic demand. Flexible Services and Manufacturing Journal, 26(1-2), 170-195.

Hong, H., Parvate-Patil, G. B., & Gordon, B. (2004). Review and analysis of variable valve timing strategies—eight ways to approach. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 218(10), 1179-1200.

Kuhlbach, K., Mehring, J., Borrmann, D., & Friedfeldt, R. (2009). Cylinder head with integrated exhaust manifold for downsizing concepts. MTZ worldwide, 70(4), 12-17.

Ladommatos, N., Balian, R., Horrocks, R., & Cooper, L. (1996). The effect of exhaust gas recirculation on combustion and NOx emissions in a high-speed direct-injection diesel engine (No. 960840). SAE Technical Paper.

Maiboom, A., Tauzia, X., & Hétet, J. F. (2008). Experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emissions of an automotive direct injection diesel engine. Energy, 33(1), 22-34.

Milanovic, R., Zhou, C. Q., Majdak, J., & Cantwell, R. (2003, January). CFD modeling of flow and heat transfer inside a liquid-cooled exhaust manifold. In Heat Transfer Summer Conference (Vol. 36959, pp. 785-792).

Neshan, M. A., Keshavarz, A., Jazayeri, A., & Ghasemian, A. (2012, May). Thermo-fluid analysis of the exhaust manifold integrated with cylinder head. In Internal Combustion Engine Division Spring Technical Conference (Vol. 44663, pp. 965-972). American Society of Mechanical Engineers.

Palash, S. M., Kalam, M. A., Masjuki, H. H., Masum, B. M., Fattah, I. R., & Mofijur, M. (2013). Impacts of biodiesel combustion on NOx emissions and their reduction approaches. Renewable and Sustainable Energy Reviews, 23, 473-490.

Plessing, T., Peters, N., & Wünning, J. G. (1998, January). Laseroptical investigation of highly preheated combustion with strong exhaust gas recirculation. In Symposium (International) on Combustion (Vol. 27, No. 2, pp. 3197-3204). Elsevier.

Potteau, S., Lutz, P., Leroux, S., Moroz, S., & Tomas, E. (2007). Cooled EGR for a turbo SI engine to reduce knocking and fuel consumption (No. 2007-01-3978). SAE Technical Paper.

Saichaitanya, P., Simhadri, K., & Vamsidurgamohan, G. (2013). Impact of Cold and Hot Exhaust Gas Recirculation on Diesel Engine. International Journal of Engineering Research and Applications, 3(5), 430-434.

Scheeringa, K., Schwerin, D., Groves, B., Zhou, C., Majdak, J., & Cantwell, R. (2002). CFD Analysis of a Liquid Cooled Exhaust Manifold. In 8th AIAA/ASME Joint Thermophysics and Heat Transfer Conference (p. 2878).

Sendzikiene, E., Makareviciene, V., & Janulis, P. (2006). Influence of fuel oxygen content on diesel engine exhaust emissions. Renewable Energy, 31(15), 2505-2512.

Su, J., Xu, M., Li, T., Gao, Y., & Wang, J. (2014). Combined effects of cooled EGR and a higher geometric compression ratio on thermal efficiency improvement of a downsized boosted spark-ignition direct-injection engine. Energy conversion and management, 78, 65-73.

Taylor, J., Fraser, N., & Wieske, P. (2010). Water cooled exhaust manifold and full load EGR technology applied to a downsized direct injection spark ignition engine. SAE International Journal of Engines, 3(1), 225-240.

Turner, J. W. G., Pearson, R. J., Curtis, R., & Holland, B. (2009). Effects of cooled EGR routing on a second-generation DISI turbocharged engine employing an integrated exhaust manifold (No. 2009-01-1487). SAE Technical Paper.

Wei, H., Zhu, T., Shu, G., Tan, L., & Wang, Y. (2012). Gasoline engine exhaust gas recirculation–a review. Applied energy, 99, 534-544.

Zelenka, P., Aufinger, H., Reczek, W., & Cartellieri, W. (1998). Cooled EGR-a key technology for future efficient HD diesels (No. 980190). SAE Technical Paper.

Zheng, M., Reader, G. T., & Hawley, J. G. (2004). Diesel engine exhaust gas recirculation—a review on advanced and novel concepts. Energy conversion and management, 45(6), 883-900.