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ISLAMIC UNIVERSITY OF TECHNOLOGY
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DESIGN AND ANALYSIS OF HEAT TRANSFER OF A FULLY SPIRAL AND SMOOTH EXHAUST GAS RECIRCULATION COOLER IN A DIESEL ENGINE.

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

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DEPARTMENT OF MECHANICAL AND PRODUCTION ENGINEERING
Islamic University of Technology
April 2022

CERTIFICATE OF RESEARCH

The thesis titled "Experimental and Numerical Investigation of heat transfer of a Full Spiral and smooth Exhaust Gas Regulation cooler" submitted by Muhammad Waqas (170011069), Hameed Ullah (17011076), Usama Javed (170011084) has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Bachelor of Science in Mechanical Engineering.

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DECLARATION

We hereby declare that this thesis titled "Experimental and Numerical Investigation of heat transfer of a Full Spiral and smooth Exhaust Gas Regulation cooler" is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Prof. Dr. Nurul Absar Chowdhury, MPE, IUT during April 2021 to April 2022.

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

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Table of Contents

Nomenclature

Symbols	**Description**
EGR	Exhaust Gas Recirculation
$\dot{m}$	Mass flow rate of fluid (kg/s)
Cp	Specific heat of fluid (J/kg)
LMTD	Logarithmic Mean Temperature Difference (℃)
K	Overall heat transfer coefficient W/m^2K
Q	Total heat transfer in the heat exchanger kJ/s
A	Area of heat ex-changer(m^2)
d_o	Outer diameter (mm)
L	length of the heat ex-changer (mm)
n	Number of tubes
D_t	Diameter of tubes (mm)
D	Diameter of shell (mm)
L_t	Length of the tubes(mm)
t_s	Thickness of shell (mm)
D	Discharge(m3/sec)
NTU	Net Transfer unit
Ɛ	Effectiveness
h	Enthalpy (kJ/kg)

Abstract

Currently our planet Earth is facing a severe climate change and the natural resources are consumed at a very vast rate, government strategies, technological companies and world organizations are working hard to reduce the emission of gases that are polluting our environment. The exhaust gas emission into the atmosphere is one of the major environmental concerns in the current days. The new emission standards for heavy vehicles and passenger cars cannot be able to meet with the adjustments to only engines. The major technique to limit the emission of these gases is to cooled down the exhaust gases, and the development of the means to reduce the formation of the Nitrogen Oxide (NO_x). Exhaust gas recirculation cooler plays a vital role in reducing the emission of exhaust gases. In this thesis study, the heat transfer characteristics of a two different types of exhaust gas recirculation coolers, of a Fully spiral EGR cooler and Full-smooth EGR cooler were computational and experimentally carried out. The heat transfer properties of two types of EGR cooler were computationally studied using a commercial software Ansys (Fluent). Experimental and computational results show that at same flow rate of the exhaust gases EGR cooler with Spiral tubes has a better heat transfer efficiency than a cooler with smooth tubes. The pressure drop in Spiral tubes EGR cooler is higher than a smooth tubes cooler. Modification of the geometrical parameters such as Effective length, tubes diameter and Spiral pitch, revolutions, depth and thickness will result in increase in performance. This study also focuses on the effect of fouling in two different types of exhaust gas recirculation coolers, it's effects and performance difference of the two different types of EGR coolers.

Keywords: Experimental and numerical study, EGR cooler, Reynold number, Nusselt Number, NTU, LMTD, Fouling of an EGR.

Chapter 1

Introduction

Engine manufacturing companies throughout the world are improving technologies to design the engines which are environment friendly, and economical. Specially diesel engine manufacturing companies are working to enhance reduction of the NO_x emission. The government policies are also bounding the companies and old vehicle users to reduce the emission of nitrogen oxide.

Nowadays, diesel fuel is replaced by an alternative fuel named as Biodiesel. The concentration of biodiesel is slightly higher than the normal diesel, and there is a complete combustion in engine for a biodiesel, because of which the combustion temperature is hinger than a pure diesel, so this is one of the reasons for the formation of nitrogen oxide. Nitrogen dioxide is formed at a higher combustion temperature, reducing the formation of NOx is possible if we can reduce the maximum combustion temperature[1]. This is possible if we can recirculate the portion of exhaust gases and reenter the cooled exhaust gases to the engine inlet, because of this recirculation the specific heat capacity of air reentering the engine is higher as well as the concentration of oxygen in air reentering the engines combustions chamber is lowered, which results in the formation of NOx [2].

Exhaust gas recirculation (EGR) system is used to reduce the emission of the nitrogen oxide NO_x. This technique is widely applicable for the industrial applications using diesel engine and diesel engine transport industry. Low-speed marine engine is also using this technique [1]. High power petrol engines also using this technique to increase the fuel consumption efficiency and to reduce the emission of NO_x and other particulate matters. To increase the performance of the internal combustion engine, the use of the efficient cooling system and cooling of the exhaust gases become necessary, before they are reintroduced to the engine via intake valve [3]. Volumetric performance of the engines requires an efficient cooling system. The cooling system is introduced in the engine compartment to lower the temperature of the engine exhaust gases, which will help reduce the temperature of the combustion chamber, results in the reduction of the NOx and particulate matters. The EGR rate also have the significant effect on the soot formation. Better the performance of exhaust gas cooler lower will be the emission.

Heat exchanger is one of the important industrial apparatuses. Thermal efficiency of the heat exchanger is normally depending on the geometric structure. For the improvement of the thermal efficiency of a heat exchanger, various researchers have worked on a lot of different geometric structures. One of most commonly used heat exchanger in the field of automotive is Exhaust gas Recirculation cooler. Smaller cross section of an EGR cooler is capable of transferring a huge amount of heat. Engine cooler performance should not be affected by the vibration of the engine [4][5].

Stehlik et al. [6] studied two types of heat exchangers, shell and tube heat exchanger with helical baffles and heat exchanger with segmental baffles, exhibit that using heat exchanger with helical baffles will result in better heat transfer. One of the major features of the helical baffle is to be able to reduce the relative pressure drop between the inlet and the exit, the pressure drops of 0.2-0.6 was seen. The modern design of a helical baffles shell and tube heat exchanger will significantly increase the heat transfer effeciency. Ozden and Tari [7] studied shell and tube heat exchanger computationally using a commercial software Ansys, they have used turbulence model for numerical simulations. Baffle spacing (between 8 and 12), baffle cut (25%, 36%) and different flow rates (0.6, 1 kg/s) were numerically studied in their work. The results predicts that the cooling system with 25% cut give more prominent results. Gao et al. experimentally studied the helical baffle and the effect of different angels were examined. Different angles of baffle (8, 12, 20, 30, 40) were considered, the heat transfer characteristics and flow parameters of a shell and tube heat exchanger were considered. The results showed that considering the same mass flow rate, heat transfer coefficient and pressure drop on the shell side of the cooler increases. The study showed that the best results are measured with a helix angle of 40.

EGR cooler is a device used to cool down the exhaust gases, before they re-enter the engine, a water is used as a cooling medium in a EGR cooler heat exchanger. The temperature of the exhaust gas is related to NOx emissions. The lower the temperature of the exhaust gas, the better the NOx suppression effect of the engine. The EGR cooler can reduce the temperature of the exhaust gas entering the cylinder. The lower temperature is definitely beneficial to the thermal load of the engine and reduces the engine temperature.

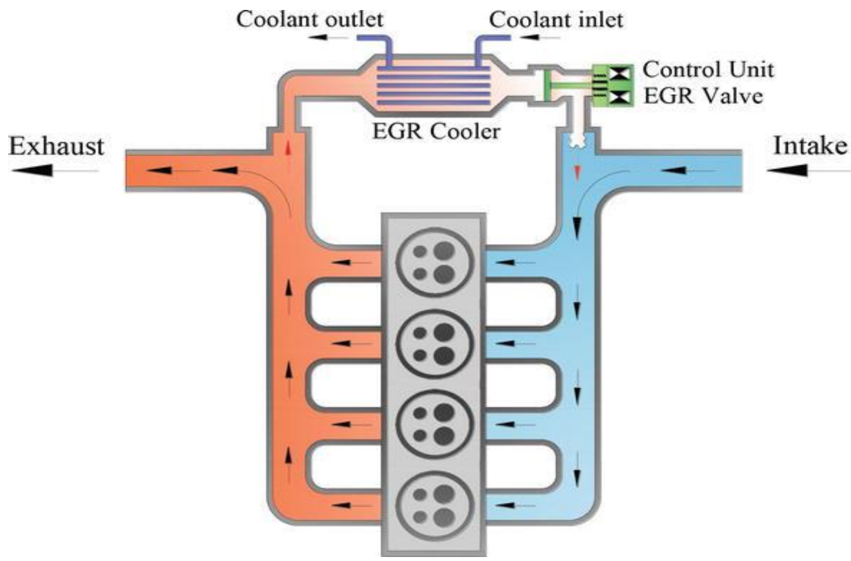


Fig.1 Exhaust Gas Recirculation system.

Internal combustion temperature of an ordinary engine reaches up to 1370℃ within the combustion chamber. During operation at higher loads, emission of NOx increases which results in reduced emission performance. The air/fuel mixture in the combustion chamber are also not completely burnable at this stage, resulting in valve chock and in extreme conditions it might be not good for engine components.

Lie et al. studied the helical baffles and fully spiral corrugated tubes exhaust gas recirculation cooler. The effect of changing the various tubes thickness, spiral and baffles were discussed considering the heat transfer and pressure drop. Experimental results were deviated from numerical results by 7.8% for pressure drop, and 7.4% for friction factor. The difference of experimental and numerical results for Nusselt number was 6.1%. The Nusselt number of tube-side is improved by 60-130% for helical baffles EGR cooler as compared with EGR with segmental baffle. Overall heat transfer efficiency is also improved.

In the present study, we have experimental and numerically studied two different types of exhaust gas recirculation cooler, with Fully spiral tubes and smooth tubes. For numerically study, a commercial software Ansys (Fluent) R19.2 was used to study the various heat transfer characteristics. 3D geometry was designed using a Solidworks software and the Parasolid binary file was imported to the Ansys software. The best exhaust gas recirculation cooler was fully spiral corrugated tubes. It was manufactured within the university workshop Lab and later experimentally tested in an automobile workshop. Numerical results were compared with experiential results.

The temperature gradient between the cold wall of the cooler and the engine exhaust gases, hydrocarbons and water vapor inside the cooler will condensate and will lead to formation of adhesive layer at the lower temperature walls of the cooler. The fouling layer reduces the efficiency of the EGR cooler. The effect of fouling is the main cause of this deposition. The term fouling can be defined as the deposition of particulate matters or other components, coming from the exhaust gases of the engine, while they are recirculating through the cooling device named as EGR cooler. The formation of thick deposit layer will result of the temperature gradient between the engine exhaust gases from the engine and the lowered temperature wall of the cooler. These layers should be removed with time, otherwise it will lower the temperature of the gases that will heat up the engine and eventually cause an engine damage.

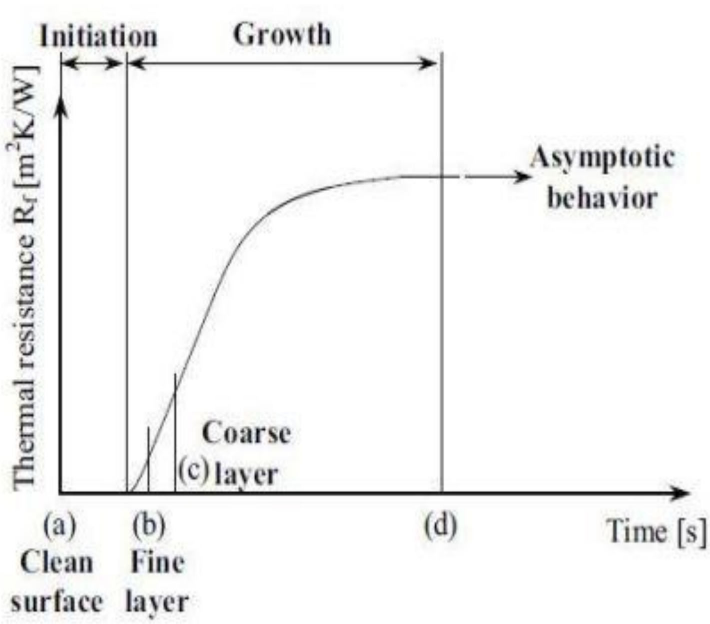


Fig.2 Thermal resistance evolution with fouling. [8]

Chapter 2

Governing Theories

Exhaust gas recirculation system is basically an emission control technology that reduces a significant amount of NOx emission into atmosphere from diesel engines. Exhaust gas recirculation (EGR) system is used to reduce the emission of the nitrogen oxide NO_x. This technique is widely applicable for the industrial applications using diesel engine and diesel engine transport industry. Low-speed marine engine is also using this technique. As we know one of the most common applications of EGR system is to NOx in diesel engine but there are various potential applications extents to other uses as well. Some major applications include imparting engine knock resistance and reducing the need of high enrichment of the fuel being used in the engine, Aiding liquid fuel vaporization in SI engines as a closed-cycle diesel engine enabler for increasing the ignition quality of difficult-to-ignite fuels or to improve the working performance of a SCR catalysts.

2.1 Exhaust Gas Recirculation cooler.

Conventional exhaust gas recirculation circuit used in the combustion engines normally consists of three fundamental parts. An exhaust gas recirculation cooler that cools down the exhaust gases coming from the engine exhaust but this cooler is different for the intercooler that is normally used in the intake air. The other important part is the EGR valve that can control the amount of the exhaust gases being recirculated. EGR valve is one of the most important parts of this system. The intermediate pipes that are used to transport gases as also the parts of this system. The EGR cooler lowers the temperature of the exhaust gases and recirculate them before reentering into the engine intake manifold. It reduces the engine combustion temperature by missing the hot recirculating air with the fresh air. The valve controls the air for entering into the circuit by the term EGR rate. The rate can be calculated by the ratio of the concentration of CO2 in the exhaust gas and the difference between the concentration of CO2 in the ambient air and the intake gas mixture in the engine [9].

$$\text{EGR Rate} = \frac{(CO2\ gm)-(CO2ambient)}{CO2\ eg}$$

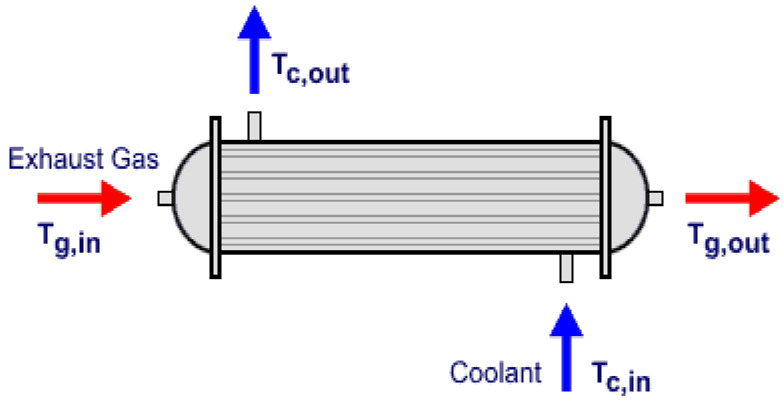


Fig: Exhaust Gas Recirculation Cooler.

The EGR cooler in simple a Heat Exchanger. The temperature of the exhaust gases is to be reduced in this cooler by the circulation of engine coolant. The exhaust gas recirculation cooler comes in a different shape and the most common type is the shell and tube. The egr cooler consists of a tubes though which the exhaust gases flow and the shell through which the coolant flows. Various types of coolers are designed to increase the effectiveness like the coolers with various types of tube fins. Maybe of rectangular, triangular or circular shapes. The circular tubes have the increased surface area and thus increased the heat transfer area which in total increase effectiveness.

Shell and Tube Heat Exchanger:

In industrial processes, heat exchangers are utilized to recover heat between two process fluids. Because of its ease of manufacture and flexibility to a wide range of working conditions, they are the most used nowadays heat exchangers in industrial operations. shell and tube heat exchanger design, comprising thermodynamic and fluid dynamic structure, estimated cost, and development, is a complex problem involving an integrated set of structural principles and practical information from a variety of regions.

Shell-and-tube heat exchangers are the most popular form of heat exchanger, and they can operate at a broad range of temperatures and pressures. They feature higher heat transfer surface-to-volume ratios than double-pipe heat exchangers and are simple to build in a wide range of length and flow arrangements. They can withstand higher pressures, and their design allows for easy disassembly for routine preservation and cleaning. Shell and tube heat exchanger are often used in refrigeration, power production, heating and cooling, chemical processes, industrial, and medicinal uses.

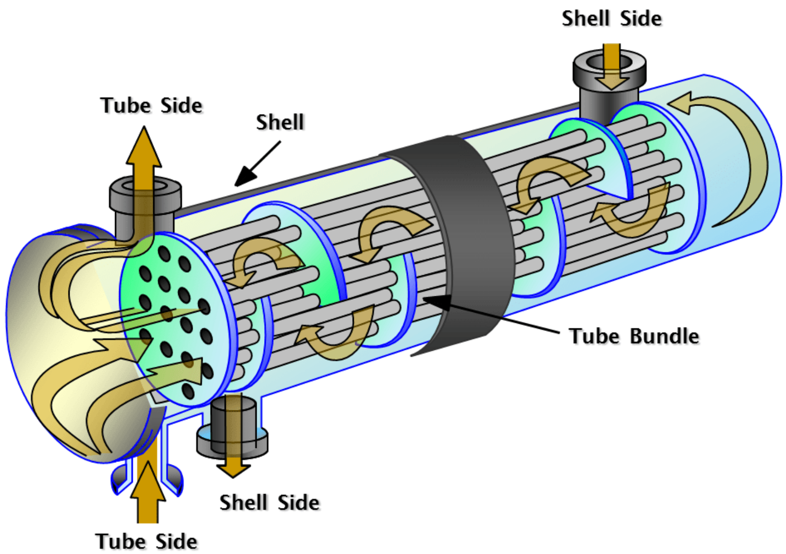


Fig: Shell and tube heat exchanger.

A shell and tube heat exchanger operates in such a straightforward way. One fluid runs through the pipes, while the other flows inside the shell. They interchange heat during moving, hence a cold fluid receives heat from the exhaust liquid. So, one liquid enters the shell inlet nozzle and exits as an exhaust fluid. Another liquid will obviously get colder at the output than the input. The visible surface zone of a STHE, which is defined by the amount of thermally conducting metal pipes, determines heat transmission. The inner part of the shell and tube heat exchanger, liquid can be either parallel or crossflow [10].

The graphic above depicts both the input and outflow nozzles in the channel's front header. That is, even the number of tubes running in this exchanger or maybe there is an odd number of tubes passes. The route side exit needle must be on the read header in such case. The heat transfer coefficient of the shell and tube heat exchange increases with increase in the no of tubes. Segmental and helical baffles are put within the shell, between the tubes respectively. The fluid roughness increases by the turbulent flow, and the fluid flows in a zigzag manner, which will result in crease in the efficiency of the heat exchanger.

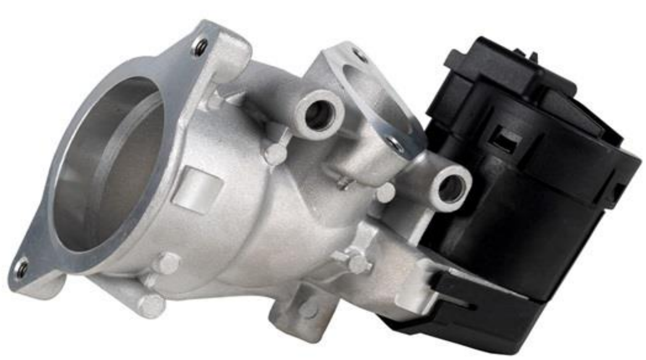
Benefits of using Shell and Tube heat exchangers:

- Optimum swimming pool heating solution, mining, equipment, pneumatic system pack, and so on.
- simple to assemble, wash and restore
- Thick in size
- These exchangers are less expensive than plate coolers.
- Effective heat transfer.

2.2 Exhaust Gas Recirculation Valve:

Air enters the internal combustion from the environment, is a mixture of Oxygen and Nitrogen, it combines with fuel and burned inside the combustion chamber and the temperature of the combustion chamber reached to about 1370°C and the normally inert gases will become reactive, creating harmful nitrogen oxides, which are then emitted to the atmosphere thorough the exhaust system. To lower this combustion temperature a small portion of exhaust gas has to be returned to the engine intake manifold and lowers the amount of NOx emission. [11].

The Exhaust gas recirculation valve is the necessary component of the EGR system and it's normally is a closed state. It provides a connection between the exhaust manifold and the intake manifold and is controlled by either a built-in electric step motor or a vacuum. The EGR valve function is to control the flow of the engine's exhaust gases being recirculated depending on the engine's load and performance.



2.3 How does an EGR valve work?

The EGR valve allows the recirculated exhaust gas in a precise manner to re-enter into the engine, effectively hanging the chemical composition of the air entering the engine. With less composition of oxygen in the air, burns slower which results in lowering the combustion temperature to about 150°C, and reducing the NOx emission. The EGR valve has two primary setting: open and closed, but the position can vary anywhere in between. The EGR valve is normally in closed position when the engine is starting up or in a rest position. During idle position or at low RPM, only a small amount of engine power is required as well as oxygen, so the EGR valve gradually opens. It can be open up to 90% at the high-power requirement. However as more power and torque are required, let say at full speed of the engine, the EGR valve gets open to ensure the maximum oxygen reaches the engine cylinders for complete combustion. As well as reducing the NOx, this valve can also be used in downsized GDi engines to improve the efficiency of engine combustion and knocking while at idle position. It can also reduce the pumping losses. With the growing environment concerns, the EGR valve will play a vital role to help reduce the emission of gases. You should know that when it fails and how to repair or replace it for proper functioning [12].

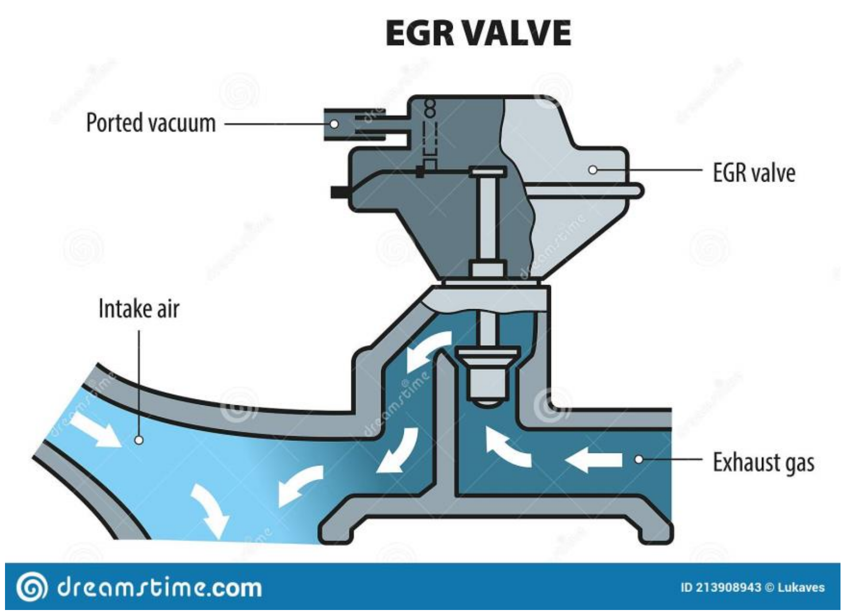


Fig. EGR valve.

Types of EGR valve:

There are several types of EGR valve available in the market, vacuum operated valve is one of the oldest techniques, while modern vehicles use electronically controlled valve. Some of the main types are broadly classified as below:

Diesel high pressure EGR valves: This type of valve diverts the high pressure flowing and high-soot exhaust gases before they enter the particulate filter. The soot may combine with oil vapor to create sludge. The intake manifold than receives the gas through a pipe.

Gasoline EGR valves: This type of valve diverts the exhaust gases same as a high-pressure diesel valve. The vacuum is created in the valve using the cylinder depression and by flowing of the exhaust gases. The EGR valve itself regulates the flow by opening and closing of the valve.

Vacuum operated EGR valve: This type of valve uses a vacuum solenoid to open and close the valve. Feedback sensor is employed in some valves to inform about the position of the valve to the electronic control unit of the vehicle.

Digital EGR valve: This type of valve uses a solenoid or a steeper motor together employed with a feedback sensor. The ECU sends a pulse width modulated signals to recirculate the exhaust gas flow.

Why do EGR valves fail?

EGR valves always operate in a hostile scenario so with time they experience a wear and tear within the valve. However, one of the major causes of failure is the formation of carbon particles from the engines exhaust gases along the EGR and the intake manifold. Over certain time this will choke the pipes, exhaust gas channels and eventually the plunger mechanism of the EGR valve. It will stick either in open or close position. The leak in the valve also causes a failure of the valve. You should must check in case of the failure of the valve otherwise, the engine will knock in the idle position because the fuel in the engine will not completely burn due to the improper supply of the oxygen. The formation of NOx will also increase and will contaminate the environment.

2.4 EGR cooler cooling principle:

Generally, heat exchanger with a liquid or a gas as a working fluid is utilized in the EGR cooling system to the cool down the exhaust cases coming from the engine. The entire circuit consists of a EGR cooler, EGR valve and the connecting pipes. The system is normally employed at the intake pipes or the engine body.

European emission standards set the bench marks for the engine manufacturing companies to meet the ECE or EUDC cycle requirements. The characteristics of the EGR cooling system are meet by the control technology of the EGR valves. Due to higher requirements for controlling accurately, the companies began to use more and more electric controlled valves. The second-generation exhaust gas recirculation system alters the efficiency of the cooling device to achieve the independent control of the gas flow and temperature, so it is the best choice for EURO IV and EURO V engines.

The entire process is very simple, it uses the hot exhaust gases coming from the engine exhaust manifold and portion of theses gases have to be cool in the exhaust gas recirculation cooler using the coolant circulating in the engine The exhaust gas recirculation cooler comes in a different shape and the most common type is the shell and tube. The egr cooler consists of a tube though which the exhaust gases flow and the shell through which the coolant flows [13].

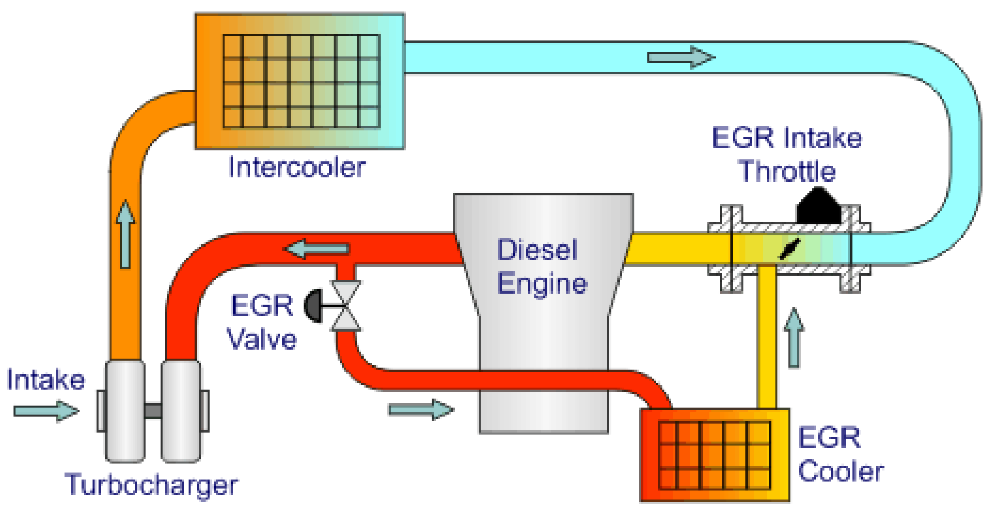


Fig. EGR cooler working principle.

Various types of coolers are designed to increase the effectiveness like the coolers with various types of tube fins. Maybe of rectangular, triangular or circular shapes. The circular tubes have the increased surface area and thus increased the heat transfer area which in total increase effectiveness. The EGR valve function is to control the flow of the engine's exhaust gases being recirculated depending on the engine's load and performance [14]. The valve controls the flow through three metering holes with increasing apertures to produce 7 combinations of the flow rate. A needle valve or a solenoid valve is used in each metering hole. When the solenoid valve is energized, it moves upward the armature, and the metering holes will become open. When the valve is in a close position, a good seal is ensured by the needle valve.

2.5 The function of EGR cooling system in the vehicle:

The function of the exhaust gas recirculation system is to reduce the NOx emission from the diesel engine to the atmosphere. At a higher RPM of the engine, a small amount of exhaust gas is recirculated into the engine for combustion. The NOx emission is related to the temperature of the exhaust gas. The lower the temperature of the exhaust gas lower will be emission of the NOx or vice versa. The exhaust gas recirculation cooler effectively reduces this temperature. The lower exhaust gas temperature is obviously advantage to the thermal load of the vehicle engine an reduces the engine combustion temperature. EGR cooler is device that meets the emission standards of the EURO 6 engines.

2.6 Fouling of an EGR cooler

Efficiency of the EGR cooler decreases with time. This is due to the deposition effect fouling. Fouling is basically the thick layer of the particles or other components originated form the engine exhaust gases being deposited on the tubes of the cooler. Thick deposit form when the exhaust gases recirculate through the EGR cooler, temperature gradient between the hot gases from the engine exhaust and the lowered temperature walls of the cooler. The particulate matter deposit on the walls of the cooler through diffusion process, thermophoresis and condensation of hydrocarbons. Fouling forms a thick resistive layer that reduces the performance of the EGR cooler. Fouling causes a significant pressure drop and temperature drop. The fouling deposits grows at a fast level at an initial stage and then growth progressively becomes slower, and eventually reaches a stable condition [15].

The thermal efficiency of the EGR coolers reduces as much as 30% with the effect of fouling in a very short time span. The deposits on the cooler surface are a mixture of unburned hydrocarbons and particulate matters in the exhaust gas, removing these deposits from the cooler surface is very hard. Deposits of particulate matters layer is less conductive than the wall of the cooler, will result in decrease in the heat transfer coefficient. Formation of fouling process with particulates and the phenomena involve that play a major role in it are show in firuge-1.

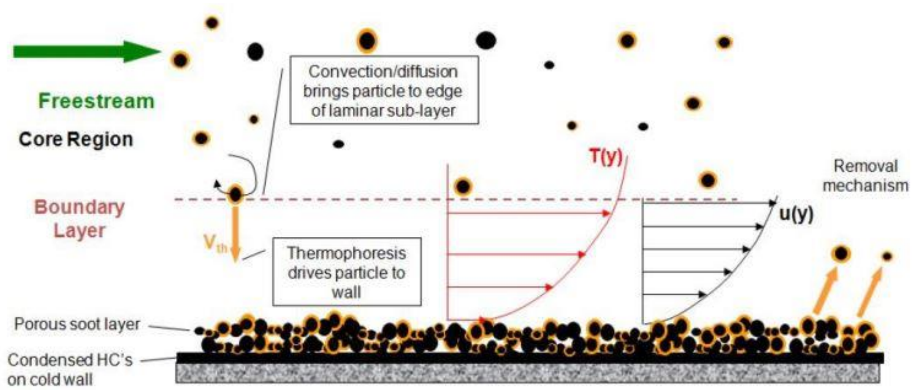


Fig. Fouling process on cooler wall.

Fouling occurs mainly due to the presence of

- soot and
- condensable particles (hydrocarbons and water vapors in the exhaust gases)

The soot deposits are in fact the particulate matters that become a source of porous deposit layer with a thermal conductivity of 0.04 W/mK. The particulate matter is one of the main components in the exhaust gases form due to the unburned fuel in the combustion chamber.

Fouling Mechanism:

Thermophoresis: Thermophoresis is a physical phenomenon, which is defined as the suspended particles in the exhaust gas moves from a higher temperature towards the lower temperature due to temperature gradient. In EGR cooler the suspended particles move toward the cooler walls.

Inside the tubes of EGR cooler, the gas in the middle of the tube has more energy than near the wall, so the suspended particles move towards the walls; thermophoresis is by far the force that weighs the most on the particles. Thermophoretic force arises as hot gas have higher velocity and the net force toward the cooler walls [13]. The correlation to obtain the drift velocity due to the effect of thermophoresis is given by,

Brock-Talbot-Correlation

$$V_{th} = -K_{th}\frac{V}{T}\nabla T = -K_{th}\frac{V}{T}\frac{\partial T}{\partial \mathrm{r}}$$

Thermophoretic coefficient K_{th} is given by

$$\mathrm{K_{th}} = \frac{2\mathrm{C_s C_c}}{(1+3\mathrm{C_m Kn})} \cdot \frac{\frac{\mathrm{k_g}}{\mathrm{k_p}} + \mathrm{C_t Kn}}{1+\frac{2\mathrm{k_g}}{\mathrm{k_p}} + 2\mathrm{C_t Kn}}$$

The factor C_c is given by,

$$C_c = 1 + Kn\,(A + Be^{-C/Kn})$$

Condensation of Hydrocarbons:

The unburnt hydrocarbon during the combustion process, due to their higher boiling point are the major component to the deposition of soot, Diffusiophoresis effect increases when the hydrocarbon condenses. There are two different types of condensation.

- Film condensation.
- Drop condensation.

Diffusion:

Diffusion occurs due to the change in trajectory of the particles due to the Brownian movement. It is a weal deposition of the soot particles. The particles move in this process through the difference in concentration.

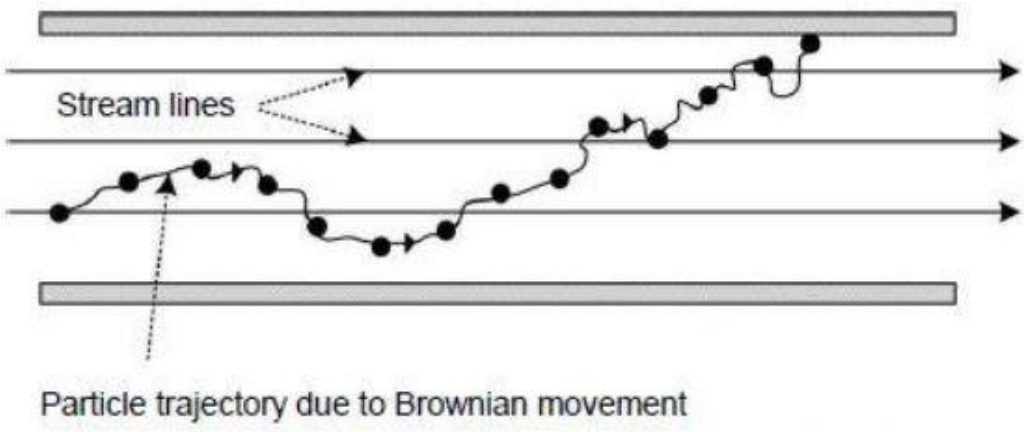


Fig. Deposition through diffusion.

For turbulent flow, it's deposition velocity is given by,

$$V_D = 0.057u^*Sc^{-2/3}$$

Where the diffusion coefficient is given by

$$Sc = \frac{v}{D_p}$$

The particle diameter is given by,

$$D_p = \frac{k_b T C_c}{3*3.14\mu d_p}$$

2.7 Term used in governing theories:

The study of the exhaust gases presents certain unique features in its physics and its behavior along with the fundamental flow characteristics. This chapter provides a comprehensive insight into these theories and how they might influence the behavior of the various design of the exhaust gas recirculation coolers.

Steady Flow

The term 'steady' implies 'no change of properties at a specific point with time'. For a flow, if the fluid properties at any fixed location does not change with time, this flow is defined to be a steady flow.

Turbulent Flow

A fluid flow which is highly disordered and is characterized by velocity fluctuations is called 'turbulent flow'. Turbulent flows typically occur at high velocities. Since air is a low-viscosity fluid having a dynamic viscosity of 1.895 x 10-5 kg/m-s at 35oC [10], the flow of air at high velocities results in a turbulent flow.

The No-Slip Condition

The no-slip condition implies that a fluid in direct contact with a surface stick to the surface and there is no slip. This means that the normal and tangential velocity components of the fluid at the surface is zero. The fluid property responsible for the no-slip condition is viscosity. This phenomenon also gives rise to the boundary layer.

The Free-Slip Condition

The free slip boundary condition is equivalent to the absence of tangential shear stress along the boundary. The free-slip boundary condition says that at the interface between a moving fluid and a stationary wall, the normal component of the fluid velocity field is equal to zero, but the tangential component is unrestricted.

The Boundary Layer

The boundary layer is a result of the no-slip condition. During flow over a surface, the layer that sticks to the surface slows the adjacent fluid layer because of viscous forces between the fluid layers, which slows the next layer, and so on. Hence, when a vertical line is considered on any point on the surface, the fluid velocity is different on every point on the line, up to a certain distance from the surface. This flow region adjacent to the wall, in which the viscous effects (and thus the velocity gradients) are significant, is called the boundary layer.

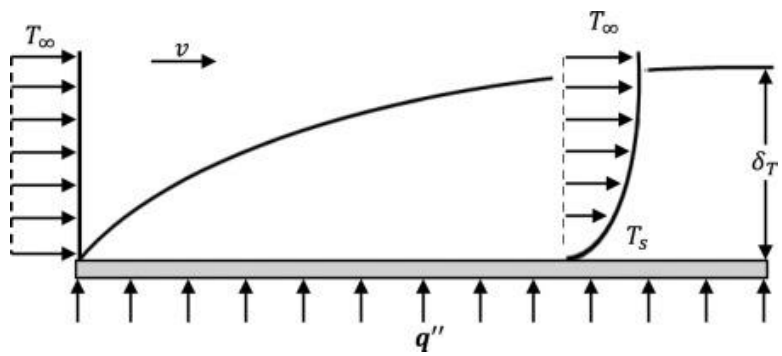


Fig. Development of the boundary layer.

Governing Equations for fluid flow:

The fundamental equations that govern fluid flow are simultaneously solved to obtain the temperature, pressure and velocity at specific points in a flow field. These equations are discussed below.

Continuity Equation

The continuity equation basically states that the rate of change of mass in a fluid flow is zero, that it is conserved. If a control volume is considered anywhere in the flow field, then, according to the continuity equation, the mass flow into the control volume would be equal to the mass flow out of the control volume. The equation is given as

$$\frac{\partial(\rho u_i)}{\partial \mathrm{t} x_i} = 0$$

Momentum equation

The momentum equation is the mathematical form of the law of conservation of momentum. It sates that the rate of change in a linear momentum of a volume moving with a fluid is equal the force acting on a body as well as surface force.

$$\frac{\partial(\rho u_i)}{\partial \mathrm{t}} + \frac{\partial(\rho u_i u_j)}{\partial \mathrm{j}} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho\, u_i{}' u_j{}'\right)$$

Energy Equation

The energy equation is the mathematical formulation of the law of conservation of energy.

$$\frac{\partial(\rho T)}{\partial x_i} + \rho \frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{y}{C_p}\frac{\partial T}{x_i}\right)$$

2.8 Why do we need Exhaust gas Recirculation system?

Before the European emission standards, the engine manufacturing companies were avoiding the emission of exhaust gases. They were not considering this into the account. Diesel engines were the one of the main reasons among others to pollute our atmosphere. After 2007, things have gone more worse so the developed countries like European Union and USA have taken the serious actions against the emission of CO2 and NOx. They have instructed the engine manufacturing companies to follow the strict protocols of environmental concerns while in a designing stage. Exhaust gases from the diesel engine contains Nitrogen Oxides (NOx), Carbon monoxide, hydrocarbons, carbon dioxide and other particulate matters. High temperature in the combustion chamber produces a lot of Nitrogen oxide NOx and release it to the atmosphere as an exhaust gas. When the air enters the combustion chamber it contains both oxygen and nitrogen, while the fuel burns both the elements combine to form nitrogen monoxide. As far as it is released it combine with air to form nitrogen oxide, which is highly a polluted gas. So, to reduce it we have to lower the combustion temperature which is possible by two ways either by jet/spark control system or by re-inserting the exhaust gases. The most continent way is to utilize the second option, which is easy and efficient. The EGR system uses the exhaust gases and recirculate them and insert those gases (5-15%) with inert air into the combustion chamber. Researchers found that 15% EGR rate is most effective in reducing the NOx emission. Our main concern in this study is to design such a EGR cooler that will reduce the engine exhaust gases so as to reduce the emission of NOx. Uses such materials for manufacturing those have good heat transfer rates.

2.9 Development of the EGR Cooler

The EGR cooler is a general application of shell and tube heat exchanger in a cold zone EGR technology. The EGR cooler comes in various shapes and materials. The working principle is same for everyone. The simplest type is smooth tubes heat exchanger, the flow in the cooler is smooth, laminar but the heat transfer efficiency is less as compared to others. The semi spiral tubes heat exchanger is then developed to enhance the heat transfer rates. Surface roughness improve the heat transfer rate but the resistance to the flow increases. Later, fully spiral tubes are designed to increase the further heat transfer. The flow in both the tubes (Spiral & Semi-spiral) is complex, the flow exists is not only axial but a secondary flow is formed the tubes path. The boundary layer cannot be formed due to the turbulent flow. Finned tubes EGR cooler is also good for the heat transfer efficiency, but the study on its design structure optimization is still under way. The use of the spiral baffles in the cheat exchanger gives a prominent result as compared to that of bow baffles. Spiral baffles are now most commonly being used in the EGR coolers. Recently, many of the researchers are working to design the high efficiency heat exchanger being used as a EGR coolers in the diesel engines. Fin-plate EGR cooler are currently under research phase. The heat exchanger is still not that good like shell and tube heat exchanger [16]. But with the deep research in this field, I hope the shortcomings of this type of heat exchange will be improved and it will become one of the prominent types of EGR cooler in the upcoming future [17].

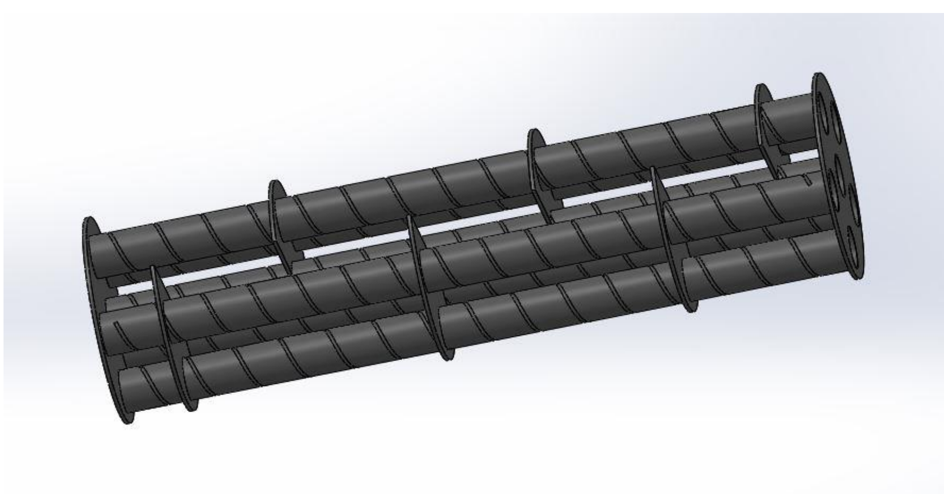


Fig. Spiral Tubes of EGR cooler.

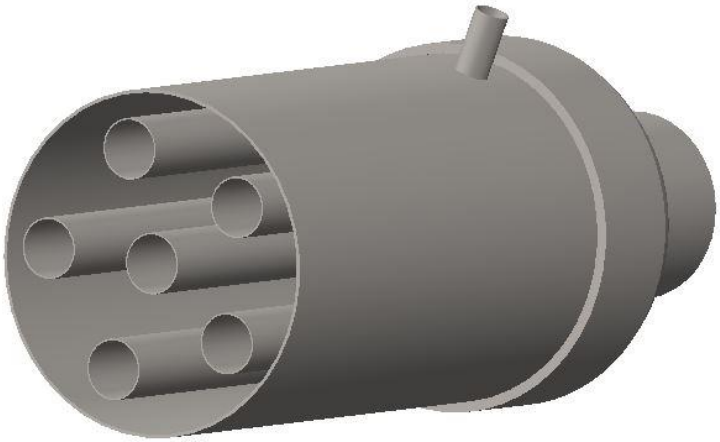


Fig. Smooth tube of EGR cooler.

The flow of the exhaust gas has normally three operating conditions. High flow is necessary during the normal RPM and cruising speeds. EGR valve is closed or only a small portion of exhaust gas is inserted due to the high oxygen requirements. Low flow is during the low RPM and light load conditions on the engine. Finally, the no flow condition is during the warm up or idling conditions. The valve is completely closed because the combustion is temperature is low as well as formation of NOx. The operating efficiency is adversely affected by the EGR valve.

Diesel engine uses the recirculated exhaust gas in order to control the emission of NOx emission. Reduction of NOx emission is primarily caused by the following main factors.

1. Recirculated exhaust gas should have the higher heat capacity than that of air. This results in lower the temperature of the combustion chamber while doing the same amount of work.
2. Partial pressure of the oxygen O_2 will be reduced, which results in lowering the mass of oxygen inside the cylinder because of air is mixed with a portion of exhaust gas having lower oxygen contents.
3. Compression ratio changes also lower the temperate of combustion.

Scope of the Study

The scope of this study is to reduce the NOx emission and to improve engine performance through various innovative ideas. The design and modification of an EGR cooler will help us to reduce the emission of NOx and to fulfil the emission standards. The study will help the industry to improve the performance of the exhaust gas recirculation cooler. It is one the main part in the exhaust system of the vehicles or diesel engines. We have designed two different types of EGR cooler using Solidworks. The first one is of smooth pipes and the other one is spiral pipes. Two different geometries are first analyzed computationally using the commercial software ANSYS. Various operating parameters are considered for investigation. We have used the Stainless-steel pipes to manufacture the EGR coolers. Fabrication has been done in the workshop lab of the university.

Experimental works are performed in the Automotive lab of the university. Data collected at different RPM and load conditions on the engine. At the end the experimental results will be compared with numerical calculations.

Chapter 3

Environmental Study

Air pollution caused by the combustion of fossil fuel causes serious concern to human health and our environment. World Health Organization (WHO) found that 9 out of 10 people in the world breathe contaminated air and more than 8 million people died because of air pollution. Exhaust gases released from the automobile engines, power plants, air crafts, ships and other transport vehicles damage human health by effecting their lungs and blood stream. In addition to this, ecosystems and biodiversity are diversely being affected by polluted air. Financial damage by air pollution has also reached a very high level. In 2015, 280$ billion has been spent on the social assistance throughout the world. Many reports and publications have been made to tackle the air pollution and many laws and standards has been developed to end the air pollution [18].

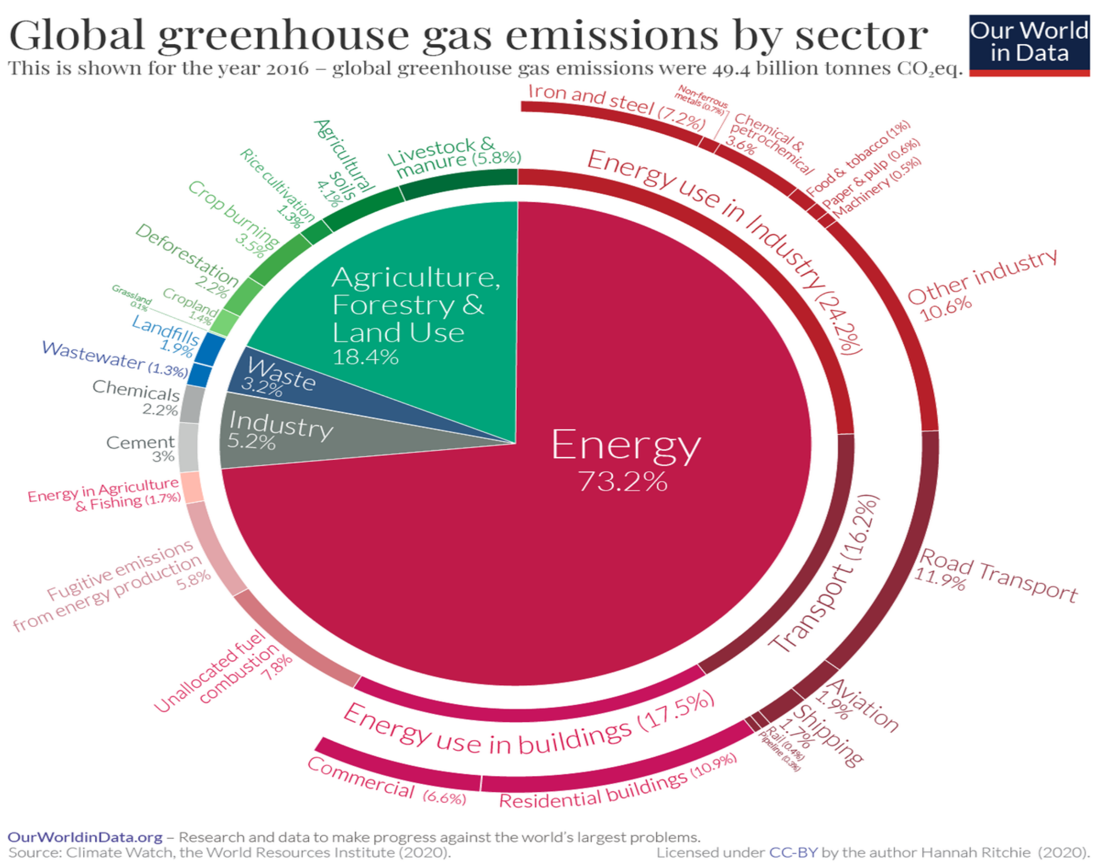


Fig. Emission of greenhouse gases.

NOx formation is one of the most important pollutants causing climate change and effecting our environment. The most effective pollutant is NOx which is destroying ozone layer. Internal combustion engines, power plants, various industry and internal combustion engines emit NOx and 95% of NOx is emitted from these sources in the world. Diesel engine are main cause of environmental pollution and a major threat to a human health. Formation of CO2, NOx, and particulate matter are causing global warming and results in increase in temperature of the Earth. The common emissions from a diesel engine can be found in this table-1.

Table. 1 Main constituents of diesel exhaust gas

Exhaust gas component	At idle	At high load
Nitrogen oxide (NOx)	50-100 ppm	600 – 2000 ppm
Hydrocarbon (HC)	50-500 ppm	< 50 ppm
Carbon monoxide (CO)	50-500 ppm	< 50 ppm
Carbon dioxide (CO2)	until 3.5 Vol-%	about 12 Vol.-%
Water vapor (H2O)	2-4 Vol.-%	until 11 Vol-%
Oxygen (O2)	18 Vol.-%	4 - 8 Vol.-%
Soot content	<50 mg m-3	50 – 120 mg m-3

3.1 European Emission Standards

The European Union first introduced the emission standards for heavy duty engine manufacturing companies in 1993. They emphasize on the reduction of NOx emission from the diesel engines to limit the impact on the human health and environment. Strict limits have been introduced to reduce the emission of harmful gases, make the engine manufacturing companies to follow the limits set by the commission. The amount of NOx emission from the heavy-duty vehicles under EURO VI standards has been reduced to

0.4 g/kWh. While Euro III standards, which was implemented in 2001, the emission was 92% higher than Euro VI engines. In 2023, it is aimed to limit the NO_x to below 0.1 g/kWh.

Table 2 EU Emission Standards for heavy-duty Diesel engines in g/kWh

Year	Reference	CO	HC	NO_x	PM
2005	EURO-4	1.5	0.46	3.5	0.02
2009	EURO-5	1.5	0.46	2.0	0.02
2013	EURO-6	1.5	0.13	0.4	0.01

The emission limit in diesel engines in Europe, particulate matter and nitrogen oxides formation in the diesel engines can be seen in this figure. Lower the nitrogen oxides emission limit higher the emission level of particulate matters.

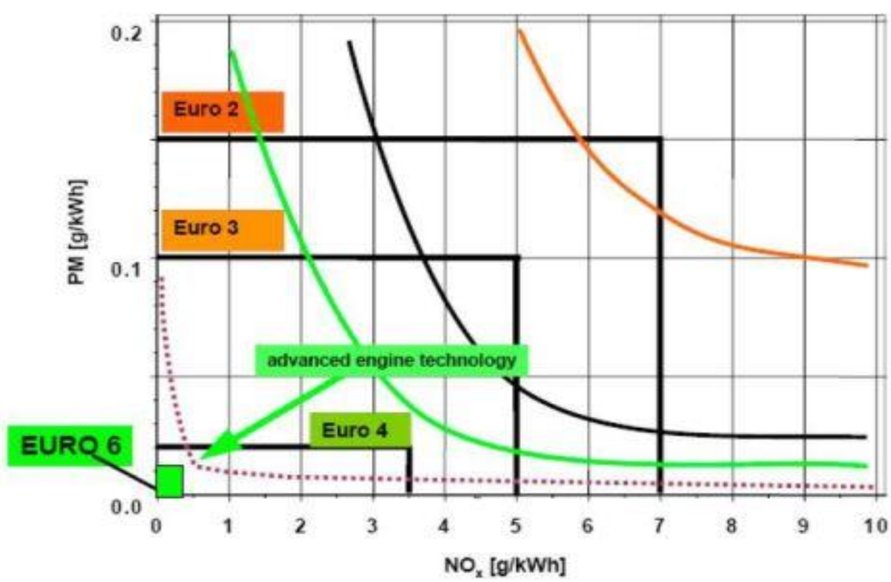


Fig. Evolution of emission standards regarding PM and NOx levels for Diesel engine.

3.2 NO_x emission from Diesel engines

There are three different formations of NO_x in diesel engines, Prompt NO_x, thermal NO_x and fuel NO_x.

$$O + N_2 \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

Emission of NO from the above reaction can be converted to NO_2.

$$NO + H_2O \rightarrow NO_2 + OH$$

$$NO_2 + O \rightarrow NO + O_2$$

Temperature and oxygen content are the basic parameters affecting the formation of NOx. When the combustion temperature increases about 1500℃, nitrogen N_2 gas in the air reacts with oxygen O_2 and forms NO_x. Increase in temperature of the combustion chamber will increase in the formation of NO_x. Each increase of 1% in combustion temperature will cause 20% increase in NO_x formation, when the temperature reaches above 1700℃.

Many research activities have taken place to eliminate NO_x from diesel engine. Different methods have been adopted to reduce the emission into pre-treatment and after-treatment methodologies. Reducing NO_x emission before reaching the exhaust port is known as pre-treatment method and reducing the emission level after the exhaust port is known as after-treatment method. Exhaust gas recirculation EGR, engine modification, water spray in combustion chamber, electronically controlled fuel injection and use of fuel additives are the pre-treatment methods of NO_x emission [19].

EGR system is one of the most effective and efficient method to incorporate the engine exhaust gases in the cylinder and mix them with the inert air during combustion process. The purpose of this system is to lower the combustion temperature and thus the NO_x emission by deteriorating the performance of the combustion process. High combustion temperature is the main influence in the NO_x formation. The Use of EGR cooler and valve reduces the oxygen concentration, which results in reducing the formation of NO_x.

Chapter 4

Experimental Study

The experimental study of the two different types of EGR cooler are performed in Automotive lab of Islamic University of Technology. At first the EGR coolers are fabricated in the workshop lab of the university. Stainless steel material with a thermal conductivity of 19.2 W/m-K and density = 7854 kg/m^3 were selected for the manufacturing of the cooler. Fully smooth tube and Fully Spiral tube are used to manufacture the EGR cooler. Bow baffles are manufactured with a stainless-steel plate. The outer shell is made of low carbon steel. EGR cooler is basically a heat exchanger device, which is used to lower the temperature of the exhaust gases coming out of the engine, which results in the reduction of NO_x. The stainless-steel pipes are cut into equal pieces to make tubes of the exchanger. Lathe operation is performed to make the external groves on the tube to make the corrugated tubes of the other type of the exchanger. Tube's structure fits inside the shell and TIG-welding are used to have a perfect leak proof cooler. After welding operation, the EGR cooler is subjected to leakage checking. Both of the coolers are leak proof for liquid and gas flow mediums.

Flow of the fluid is measured using the 2L of water bottles, time recorded to fill the water bottle, in this way mass flow rate of water has to be measured. Water pump of capacity 10L/min is used to circulate the water or a cooling medium inside the shell.

Components of an EGR system:

1. Corrugated tubes
2. Shell
3. Baffles
4. Coolant pump
5. Channel covers
6. Thermometer and thermocouples.

Table-3 Geometry of EGR Cooler.

Spiral EGR cooler	Dimensions and description	Smooth Tubes EGR cooler	Dimensions and description
Material	316 Stainless-steel	Material	316 Stainless-steel
Tubes number	6	Tubes number	6
d_o/d_i (mm)	19.05/17.55	d_o/d_i (mm)	19.05/17.55 (3/4”)
Spiral angle	134°	Spiral angle	No spiral
Revolutions	18	Revolutions	No spiral
Pitch	14.15	Pitch	No spiral
Effective length (mm)	304.8	Effective length (mm)	304.8
Shell (D_o/D_i) (mm)	102.6/99.6	Shell (D_o/D_i) (mm)	102.6/99.6
Baffle thickness (mm)	3.5	Baffle thickness (mm)	3.5
No of baffles	3	No of baffles	3

4.1 Design and Fabrication of various parts of EGR cooler.

Corrugated tubes: Corrugated tubes of the cooler are one of the fundamental parts of the EGR cooler. They provide a heat transfer surface between the shell side fluid and the tube side fluid. The material chosen for the fabrication of the corrugated tubes should be highly thermal conductive to provide the better heat transfer between the hot and the cold fluid. We have used the stainless steel with a thermal conductivity of 19.2 W/m-K and density = 7854 kg/m^3. The tubes are welded with the end channel plates to provide the leakproof surface. External grooves are made on the stainless-steel pipes using the threading operation on a center lathe machine. Groves provide a better heat transfer surface due to the turbulent flow over the corrugated surface.

Heat transfer efficiency is approximately 65% for EGR cooler using corrugated tubes as compared to 52%, for EGR cooler with smooth tubes (shell and tube heat exchanger).

The reason for the better heat transfer efficiency is, the heat transfer area increases on corrugated tubes and turbulent flow extract more heat from the tubes as compare to smooth tubes. We have used 6 corrugated tubes in the geometry.

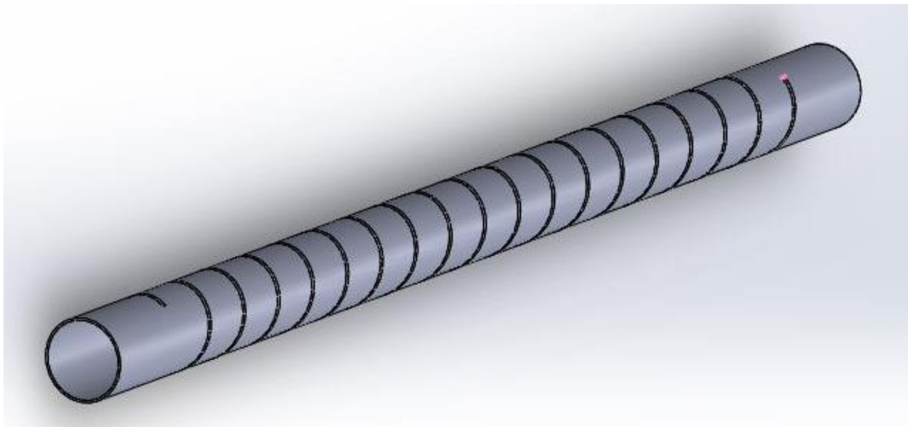


Fig. Corrugated tubes Solidworks model.

Fig. Machined corrugated tubes and baffles.

Shell: The shell is of circular cross section and is used to contain the coolant fluid, covers the tube's structure and the main body of the EGR cooler. The material used for the shell side is low carbon steel alloy.

Fig. Shell

Baffles: Baffles are used in the EGR cooler to support the corrugated tubes during assembling and operation. Baffles servers the important purpose of directing the fluid in a zigzag pattern within the shell and lower the high pressure of the coolant. This will result in increase in velocity and heat transfer efficiency. In the experiment we have used 3 baffles.

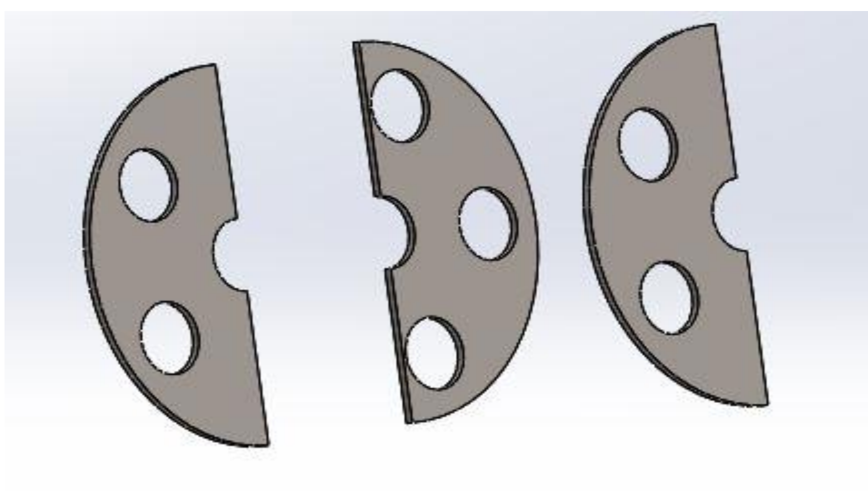


Fig: Segmental baffles.

Tubes layout: Layout of the tubes in the EGR cooler is very important. Heat transfer efficiency is greatly affected by the tube's layout within the shell. Equilateral triangle between each three tubes provides a perfect arrangement, this will result in smaller cooler with more heat transfer rates.

Fig. Tubes layout.

Coolant Pump: Coolant pump is used to supply the coolant fluid to the shell, to cool the exhaust gases flowing in the corrugated tubes. In this experiment we have used a small submersible pump, power rated 8w and 12V DC, with a maxiumum flow rate of 10L/min.

Fig. Coolant pump.

Thermometer and thermocouple: Thermometer and thermocouples are used to measure the temperatures at the inlet and outlet position of the shell and tubes. We have used four K-type (Chromega Alumega) thermocouples with a temperature range of -27℃ to 600℃.

Fig. Spiral Tubes and baffles arrangement.

Stainless steel spiral tubes and baffle are machined and fabricated in IUT workshop lab with the help of lab instructors. Hot exhaust gases will flow inside of these corrugated pipes.

Threading operation on a center lathe machine has been performed in a workshop lab to make external groves on a stainless-steel pipe.

Fig. Machining operation a center lathe machine.

4.2 Experimental setup:

The objective of this experiment was to investigate the heat transfer characteristics and fluid flow parameters of a smooth tubes and fully spiral shell & tube EGR cooler. In order to achieve this goal, we have used two separates 4-cylinder diesel engine vehicles. One is 1800cc and the other one is 2698cc. The EGR cooler connects the exhaust port of the engine. Tubes sides receive exhaust gases from the engine and the shell side receive coolant. Four K-type thermocouples (Chromega Alumega) with a temperature range of -27℃ to 600℃ were used to measure the temperature of the inlet and outlet ports. Temperature data were recorded using a 305p-type thermometer. The flow rate of the cooling liquid is measured by a water bottle of 2L, stop watch was used to calculate the time to fill the bottle. The RPM of the engine was calculated using a vehicle RPM meter. Data was calculated at various engine RPM and constant load conditions. Results shows a significant reduce in temperature of the exhaust gases using a corrugated tubes heat exchanger.

4.3 Procedure of the experimental studies.

Experiment was performed in the Automobile lab of the university. After fabrication of the two different types of EGR cooler, they were experimentally tested in two different vehicles. The tube side inlet is connected with the engine exhaust gases and the cooling water is connected to the inlet of the shell. The outlet of the egr cooler is connected with the EGR valve. Four thermocouples are connected at the inlet and the outlet of the egr cooler. Data was collected on the 305p-type digital thermometer. Water pump is used to supply the cooling water to the shell of the egr cooler to cool down the exhaust gases flowing within the corrugated and smooth tubes. Flow rate of the water is calculated with the help of stopwatch and 2L bottles. The temperature of the cooling water is kept constant at 27℃. Since the best performance of EGR is at part load, The EGR cooler performance was tested at various RPM of the engine and at part loads. The different EGR ratios are 10%, 20%, 30%. The difference between the inlet and outlet temperature of the cooling water has to be determined, as well as the temperature difference between the exhaust gases inlet and outlet. Heat transfer efficiency, effectiveness and overall heat transfer coefficient are determined using various theoretical formulas.

Fig. Experimental setup.

4.4 Data from the experiment:

Table- 4 Fully spiral tubes EGR cooler. (Counter flow)

No of Obs	Time (s)	Gas Inlet ℃	Water Inlet ℃	Gas Outlet ℃	Water Outlet ℃	RPM	Mass flow rate (Water)	Velocity (Gas) m/s
1	29.2	99	27	72	34	1500	0.06	4.32
2	30.1	110.1	27	83.4	33.9	1600	0.067	4.42
3	30.1	117.4	27	91.3	37.4	1700	0.067	4.67
4	30.1	123.6	27	97.4	40.2	1850	0.067	5.05
5	30.1	134.2	27	103.9	43.7	2000	0.067	6.27

Table-5 Smooth tubes EGR cooler. (Counter Flow)

No of Obs	Time (s)	Gas Inlet ℃	Water Inlet ℃	Gas Outlet ℃	Water Outlet ℃	RPM	Mass flow rate (Water)	Velocity (Gas) m/s
1	23.94	94	27	75	32	1500	0.08	4.32
2	24.6	108	27	90.4	33.2	1550	0.081	4.39
3	24.6	117.2	27	94.6	35.5	1700	0.081	4.65
4	24.6	123.5	27	102.7	40.9	1800	0.081	4.98
5	24.6	132.1	27	110.3	41.2	2000	0.081	6.47

Data from the experiment:

Table- 4 Fully spiral tubes EGR cooler. (Parallel flow)

No of Obs	Time (s)	Gas Inlet ℃	Water Inlet ℃	Gas Outlet ℃	Water Outlet ℃	RPM	Mass flow rate (Water)	Velocity (Gas) m/s
1	28.7	97.3	27	76.2	32	1500	0.06	4.29
2	30.4	112.1	27	87.4	32.9	1600	0.067	4.39
3	30.4	116.5	27	94.3	36.4	1700	0.067	4.65
4	30.4	121.4	27	99.8	39.1	1850	0.067	5.12
5	30.4	135.8	27	110.9	41.2	2000	0.067	6.12

Table-5 Smooth tubes EGR cooler. (Parallel flow)

No of Obs	Time (s)	Gas Inlet ℃	Water Inlet ℃	Gas Outlet ℃	Water Outlet ℃	RPM	Mass flow rate (Water)	Velocity (Gas) m/s
1	23.94	92	27	77.3	34	1500	0.06	3.78
2	24.6	107.1	27	92.1	33.9	1550	0.067	4.39
3	24.6	116.3	27	95.6	37.4	1700	0.067	4.54
4	24.6	124.1	27	105.7	40.2	1800	0.067	5.11
5	24.6	129.1	27	108.4	43.7	2000	0.067	6.34

Standard Assumptions

Mass and energy conservation of a particles require the following standard assumptions:

- Coolant temperature is kept constant (300K)
- The density of the exhaust gas is assumed to be 1.293kg/m^3 @ 273K and 101325 Pa.
- Temperature of the walls of the cooler are constant.
- Gas properties may vary with change in temperature.
- Fouling doesn't vary with temperature and soot deposit are negligible.
- Adiabatic wall conditions were considered for the outer shell walls and the pressure was taken as atmospheric (P_{atm} = 101325 Pa).

4.5 Experimental Calculations:

Heat transfer from the exhaust gas

$$Q_{ex} = m_{ex} x \Delta T_{ex}$$

$$\Delta T_{ex} = T_{ex.out} - T_{ex.in}$$

Specific heat capacity of the exhaust gases C_p = 1.007KJ/kgK

Mass flow rate of the exhaust gas can be determined,

$$m_{ex} = \rho A V_{exhaust}$$

Where ρ is density of the exhaust gas, A through which the gas is flowing, V is the velocity of the gas measured through taco meter.

Similarly, heat transfer from the coolant water,

$$Q_{cw} = m_{cw} x \Delta T_{cw}$$

$$\Delta T_{cw} = T_{cw.out} - T_{cw.in}$$

The actual heat transfer of EGR cooling system can be considered as the average heat transfer of the cooling side and exhaust gas side.

$$Q = \frac{Q_{ex} + Q_{cw}}{2}$$

Heat transfer effectiveness

The amount of heat transfer effectiveness is given by,

$$\mathcal{E} = \frac{Q}{Q_{max}}$$

$$Q_{max} = C_{min}\,(T_{ex.in} - T_{cw.in})$$

$$C_{min} = Minimum\ heat\ capacity\ rate$$

$$C_{max} = Minimum\ heat\ capacity\ rate$$

$$C_{min} = m_{ex} C_{p.ex}$$

$$C_{max} = m_{cw} C_{p.cw}$$

Log mean Temperature difference for Shell and tube EGR cooler as counter flow heat exchanger.

$$\textbf{LMTD},\ \Delta T_m = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}}$$

Where ΔT_1 is the difference between the hot gas inlet and cold outlet, and ΔT_2 is the difference between the hot gas outlet and cold inlet.

$$\Delta T_1 = T_{ex.i} - T_{cw.o}$$

$$\Delta T_2 = T_{ex.o} - T_{cw.in}$$

Overall Heat transfer coefficient

To determine the overall heat transfer equation,

$$A_o = \frac{Q_{avg}}{U_o \Delta T_m}$$

U_o is the overall heat transfer coefficient, Q_{avg} is the average heat transfer between the hot and cold medium and ΔT_m is the log mean temperate difference.

A_o = Outside heat transfer surface area. (m^2)

$$A_o = \pi N_t d_o L = 0.1094\, m^2$$

N_t = Number of tubes in an EGR cooler

D_o = outer diameter of the tubes (mm)

L = length of the tubes. (mm)

So, **Overall heat transfer coefficient** is given by,

$$U_o = \frac{Q_{avg}}{A_o \Delta T_m}$$

Heat transfer coefficient of the water side is given by,

$$h_o = j_H \frac{k}{D_e} \frac{\mu C_p}{k}\ x\ \varphi$$

J_H is a dimensionless factor in the design and performance prediction of the heat exchanger, thermal conductivity of water at average temperature is k = 0.63 W/mK.

De is the equivalent diameter.

$$D_e = \frac{4a_s}{wetted\ perimeter}$$

Where, a_s is the flow area, $a_s = a_{shell} - a_{tubes}$

Reynolds number is given by,

$$Re = \frac{\rho VD}{\mu}$$

Nusselt number is given by,

$$Nu = h_o \frac{D_e}{k}$$

Where, h_o is the heat transfer coefficient for shell and tube side, Delaware method can be used for calculating shell side heat transfer coefficient.

4.6 Experimental Results

Spiral Tubes (Counter Flow)

No of obs	Q_{ex}	Q_{cw}	Q Watts	Ɛ %	LMTD	U_o W/m^2K	Re	Nu
1	435.44	4.56	307.57	57.3	54.38	51.69	1754	32.062
2	475.4	5.94	324.68	58.3	65.80	45.103	1794	32.40
3	503.45	6.23	405.71	58.7	71.86	51.607	1890	33.486
4	591.34	7.54	582.52	61.5	76.71	69.413	2050	36.05
5	662.44	7.87	651.43	64.9	83.51	71.30	2546	41.338

Smooth Tubes (Counter Flow)

No of obs	Q_{ex}	Q_{cw}	Q Watts	Ɛ %	LMTD	U_o W/m^2K	Re	Nu
1	427.43	4.13	301.6	47.3	54.70	51.70	1754	32.062
2	466.43	5.32	314.48	48.5	68.94	41.69	1776	32.89
3	496.43	5.89	398.31	51.4	74.42	47.78	1885	34.169
4	581.23	6.98	577.12	53.23	76.77	57.71	1987	35.34
5	649.34	7.34	643.02	55.47	87.04	66.52	2576	41.64

4.6 Graphical representation of the Results.

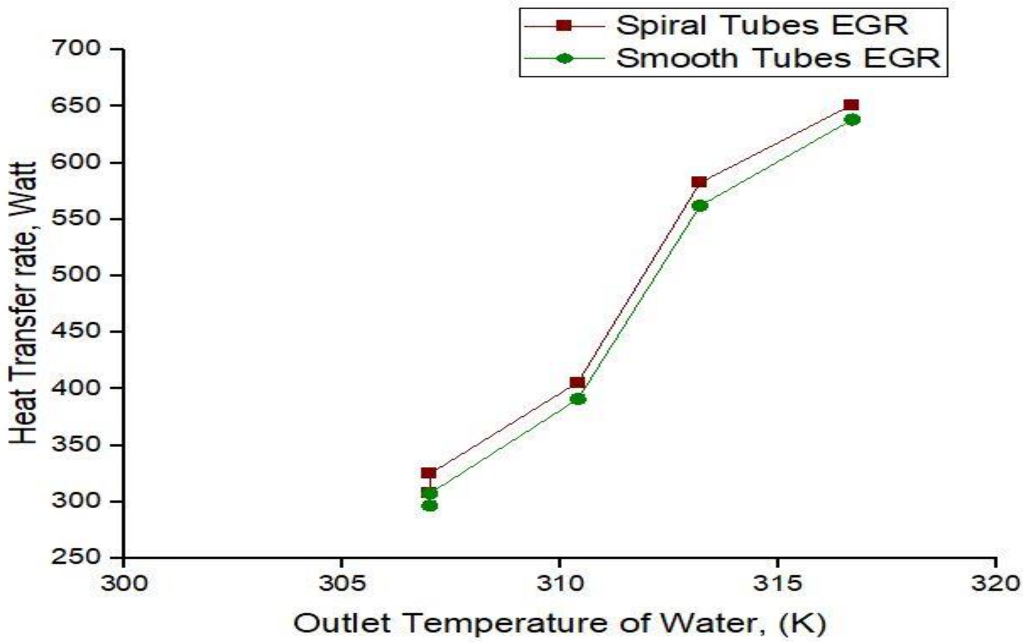


Fig. Heat Transfer Rate variation.

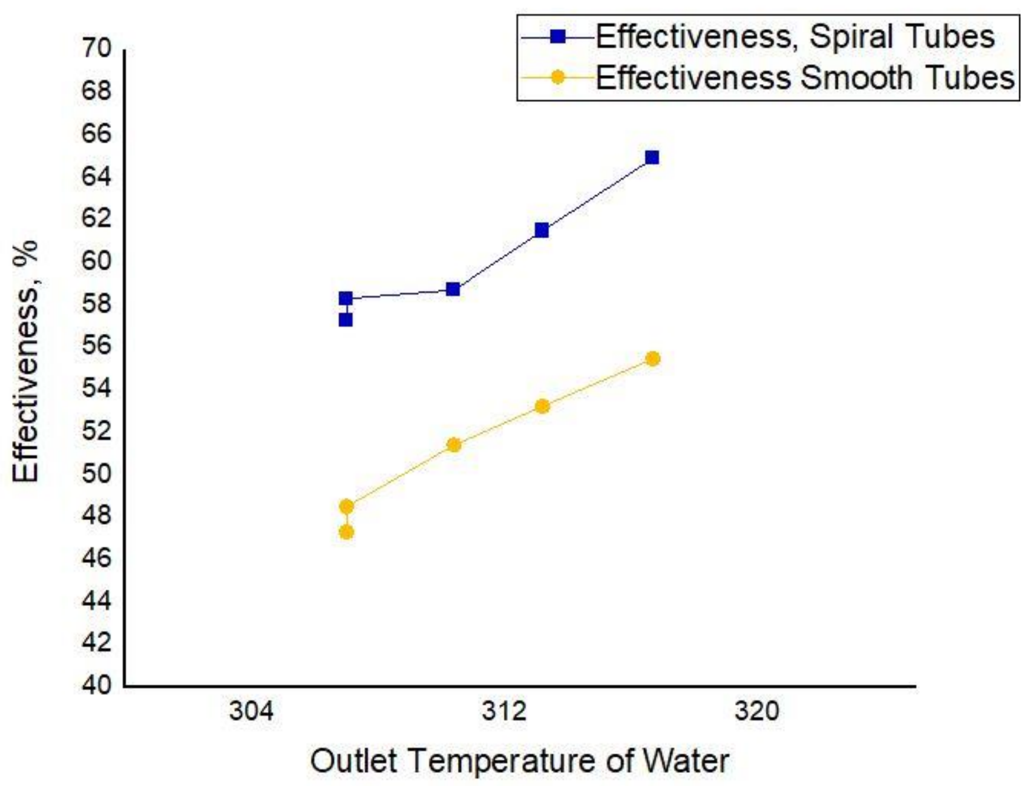


Fig. Effectiveness variation.

Nusselt number for the tube-side of the fully spiral EGR cooler and smooth tubes EGR for tube-side are shown in Fig. 1. Nusselt number for the spiral EGR cooler is higher than the smooth tubes.

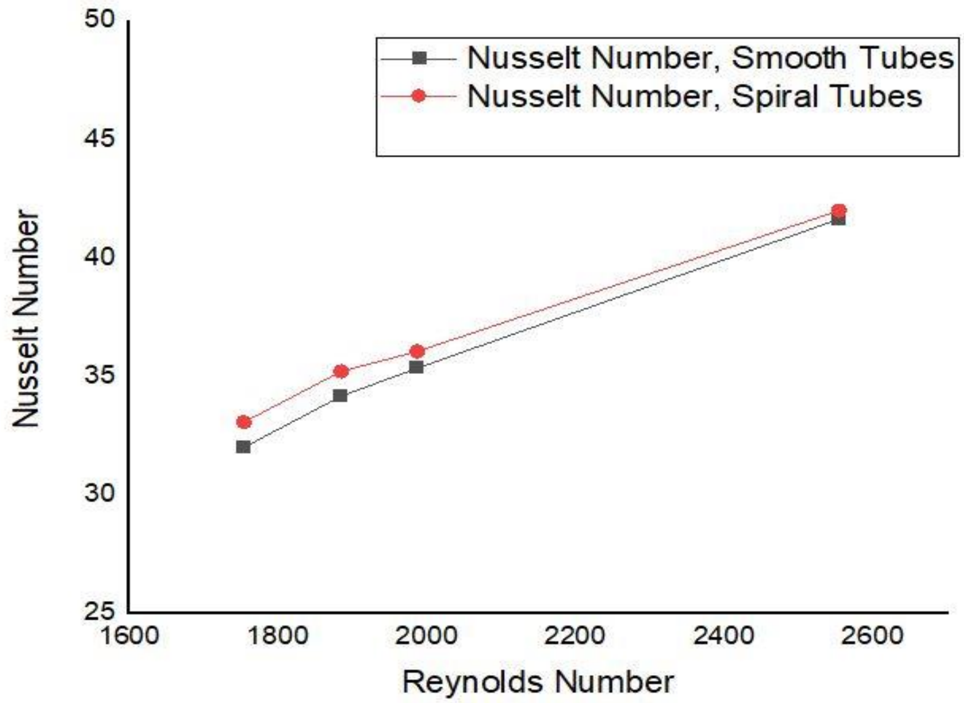


Fig. Nusselt Number variation.

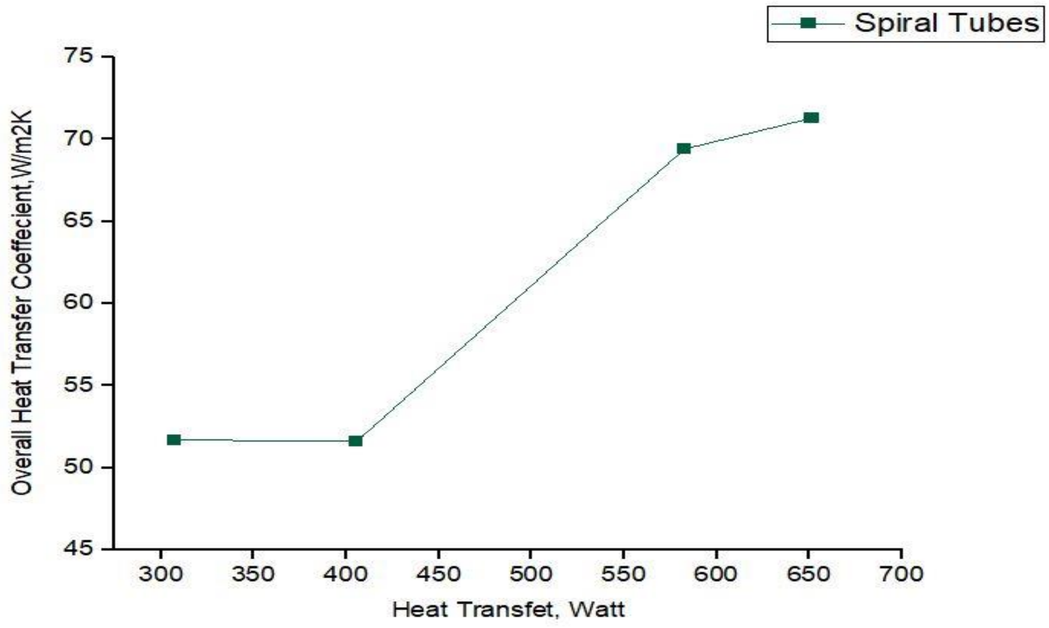


Fig. Overall Heat Transfer Coefficient variation.

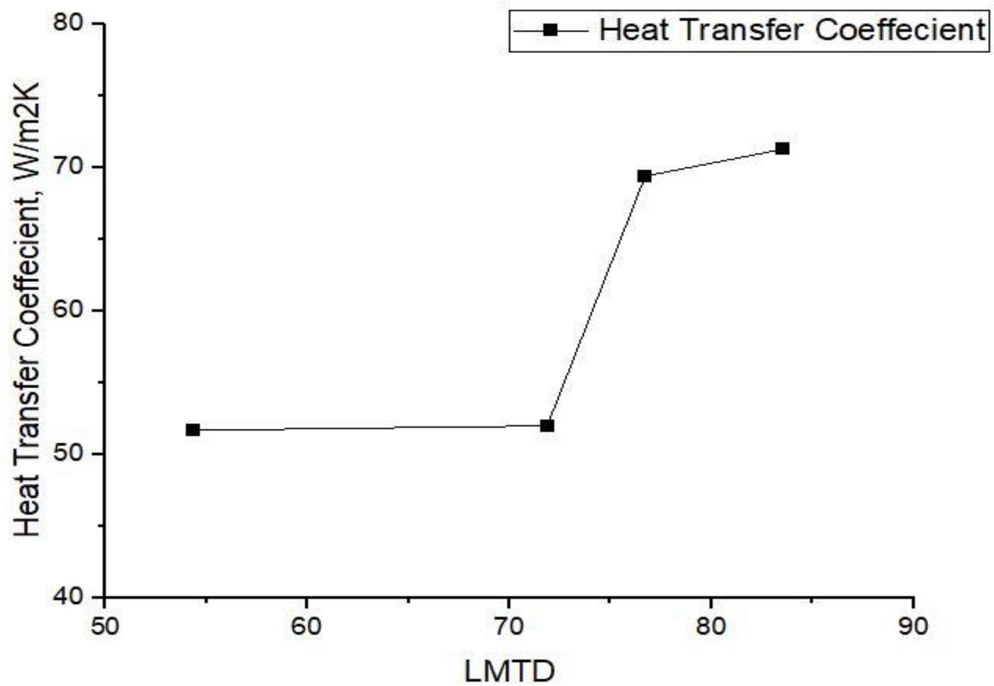


Fig. Heat Transfer coefficient variation.

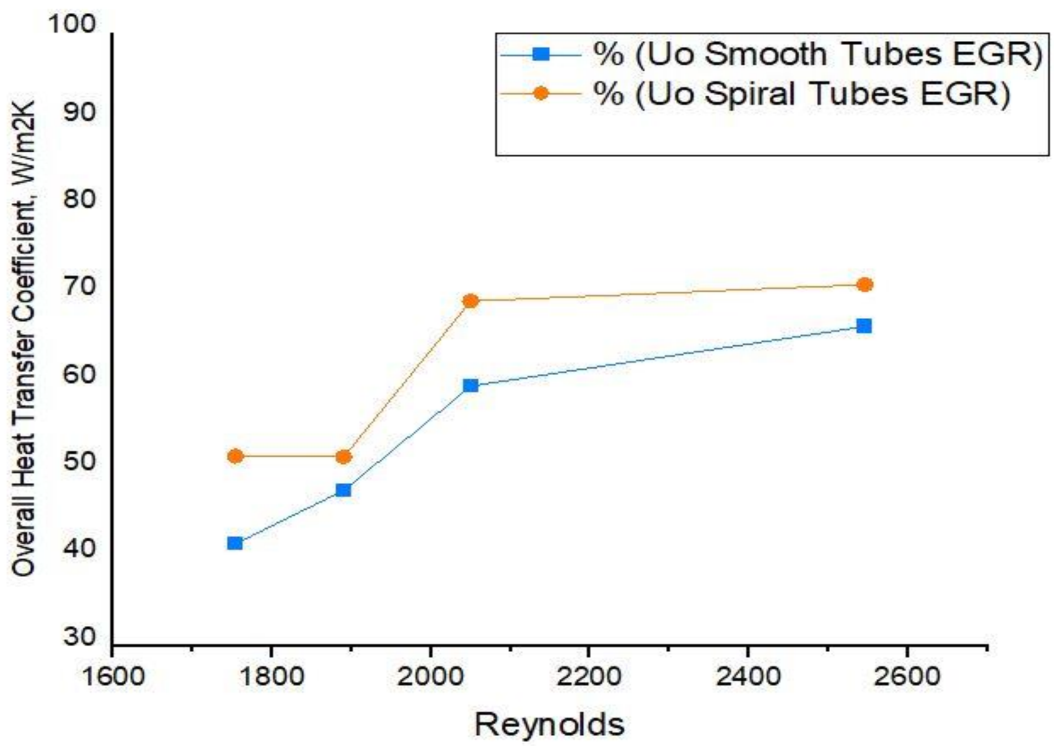


Fig. Overall Heat transfer coefficient.

Our main objective was to design an EGR cooler that will increase the heat transfer efficiency. So, in the graph below it is clear that the designed EGR cooler in the study increase the heat transfer efficiency by approx. 2%. This will help reduce the NO_x further.

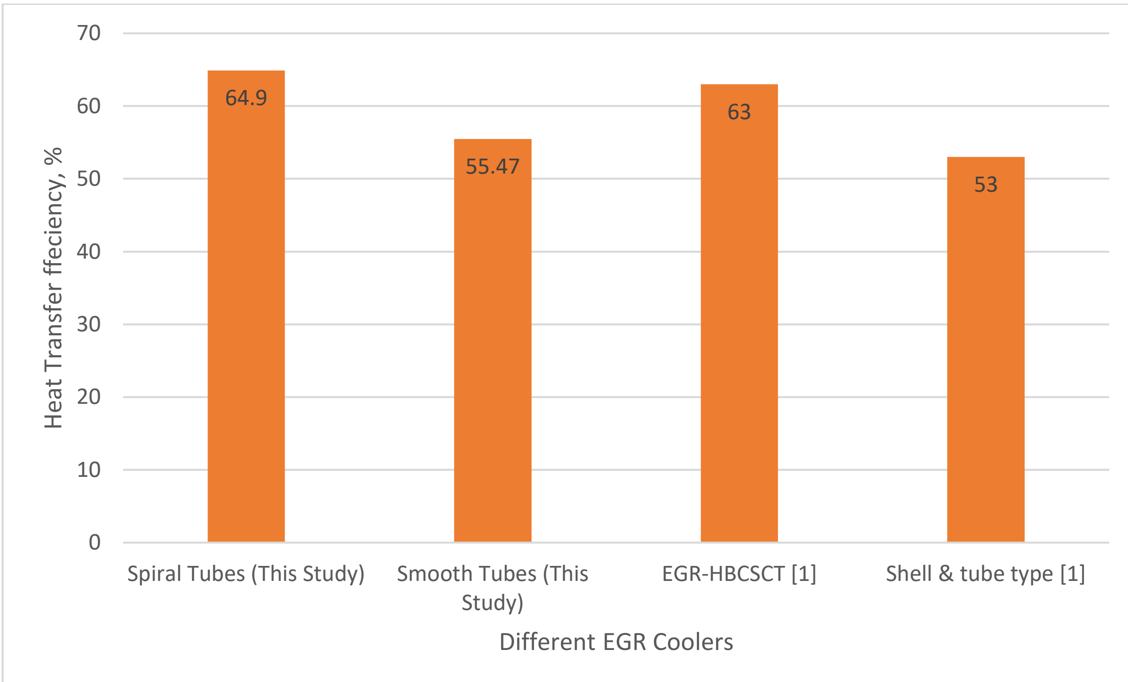


Fig. Heat Transfer efficiency variation.

Chapter 5

Numerical Methodology

Numerically study is performed considering a 3D modeling technique using a computational fluid dynamic code, of commercially available software ANSYS Fluent. The main objective of this study is to enhance the heat transfer performance and turbulence characteristics of an EGR cooler. Several mathematical equations were used while performing the simulation. Conjugate heat transfer is considered, as there is solid-fluid interaction within the cooler. Turbulence equations were also considered for the simulation work.

Numerical Models

For the simulation of heat transfer and fluid flow of the two different types of exhaust gas coolers, three-dimensional **K-Ɛ turbulence** model was used. The Second order upwind scheme discretization was used to solve the momentum, turbulence, pressure and least squares cell-based solver was used to perform the simulation. To determine the stability of the results, several results were plotted.

Mathematical calculations

Three basic equations were solved numerically in this study, which are as under;

Continuity equation can be expressed as;

$$\frac{\partial(\rho u_i)}{\partial \mathrm{t} x_i} = 0$$

Momentum equation can be expressed as;

$$\frac{\partial(\rho u_i)}{\partial \mathrm{t}} + \frac{\partial(\rho u_i u_j)}{\partial \mathrm{j}} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho\, u_i' u_j'\right)$$

Energy equation can be expressed as;

$$\frac{\partial(\rho T)}{\partial x_i} + \rho \frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{y}{C_p}\frac{\partial T}{x_i}\right)$$

Three-dimensional K-Ɛ turbulence model was used to simulate heat transfer and fluid flow, using the following equations;

$$\frac{\partial(u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma k}\right)\frac{\partial k}{\partial x_i}\right) + \phi - \varepsilon$$

$$\frac{\partial u_i \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma \varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + c_1 \phi \varepsilon - c_2 \frac{\varepsilon^2}{k + \sqrt{\mu \varepsilon}}\, \varepsilon$$

Geometry Model

Properties of a physical model of the two types of EGR cooler are shown in table.

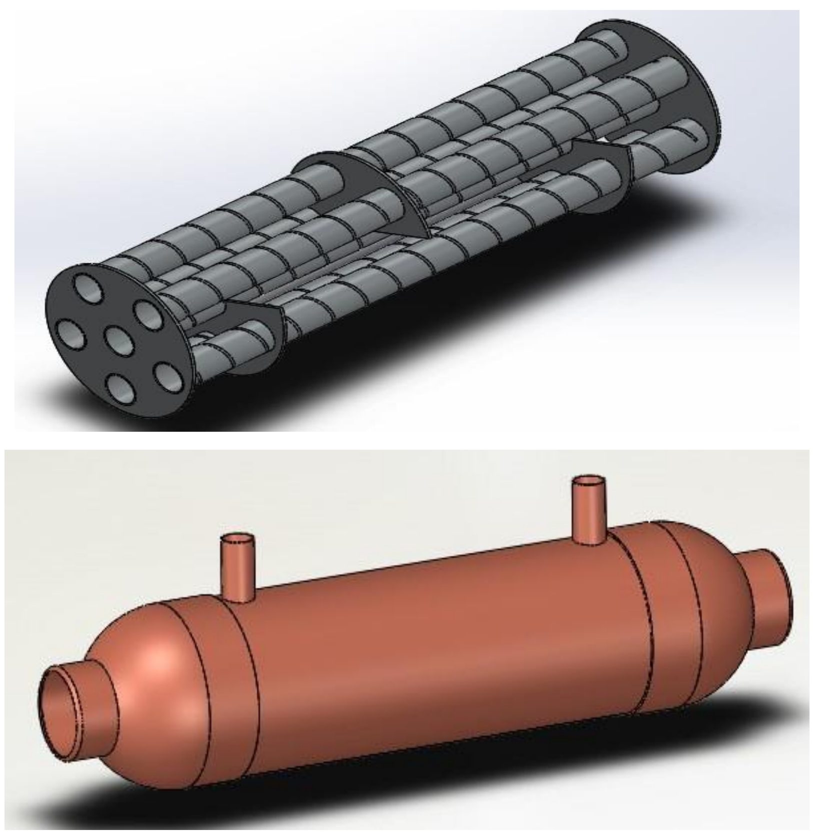


Fig. Spiral Exhaust Gas Recirculation cooler.

Meshing of the geometry

Meshing is the most important part in determining the accurate results. Tetrahedral method is applied for the outer part of the shell and hexagonal method is applied to the shell side water fluid domains to ensure the fine quality of mesh for better convergence. The element size is around 0.001m and a high quality was selected. Mesh metrics is skewness. Local mesh refinement and wall treatment were performed to ensure the fine quality of mesh. The total number of elements for the spiral geometry was around 6145301 (6million) and the no of nodes were 186503. The no of elements for smooth geometry was around 5234321 and the no of nodes were 98475.

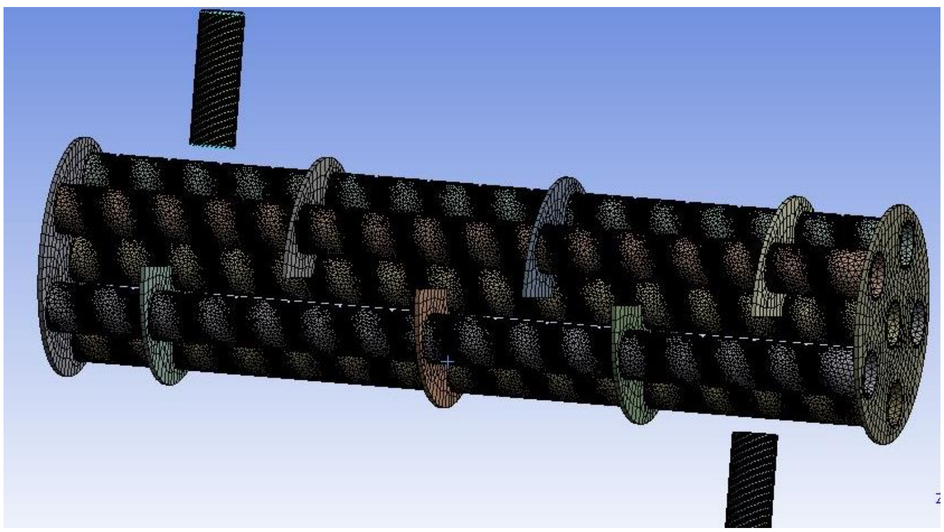


Fig. Meshing of the EGR cooler geometry.

Boundary Conditions

After meshing of the geometry, the EGR cooler geometry was set up for CFD simulation. Boundary conditions are important to get the desired results. Working fluid in the tubes section of the cooler was engine exhaust gas (Carbon Oxide Nitrogen) passes at a speed of 8 m/s and a temperature of 417K. The density of gas was considered (1 kg/m^3) and the thermal conductivity is 0.0454 W/mK. The working fluid in the shell side of the cooler is cooling water. Which flows in a counterflow direction of the gas flow. The density of the water is 997 kg/m^3. The inlet temperature of the water was kept constant 27℃ and velocity as 0.6 m/s. The material used for the geometry was stainless steel with a thermal conductivity of 50 W/mK.

Adiabatic wall conditions were considered for the outer shell walls and the pressure was taken as atmospheric (P_{atm} = 101325 Pa).

Table-5 Boundary conditions

Boundary Condition	**Type of Condition**	**Description**
Shell side Inlet	Velocity Inlet (Velocity is normal to area)	9 m/s Temperature =300K
Shell side Outlet	Pressure Outlet	Pressure =0 Pa
Tube side Inlet	Mass Flow Inlet	0.4 kg/s & T= 407K
Tube side Outlet	Pressure Outlet	Pressure = 0 Pa
Material (Steel)	Stainless steel conductivity	50 W/mK.
Shell side w. fluid	Water	ρ=997 kg/m³.
Tube side w. fluid	Exhaust Gases	ρ=1 kg/m³.

Computational Results and Discussion:

Pressure Distribution

The pressure distribution, of the exhaust gas recirculation cooler at the same mass flow rate is shown in the Fig. 22. Pressure distribution contour shows, pressure drop is significant on the shell side of the cooler as compared to that on the tube side.

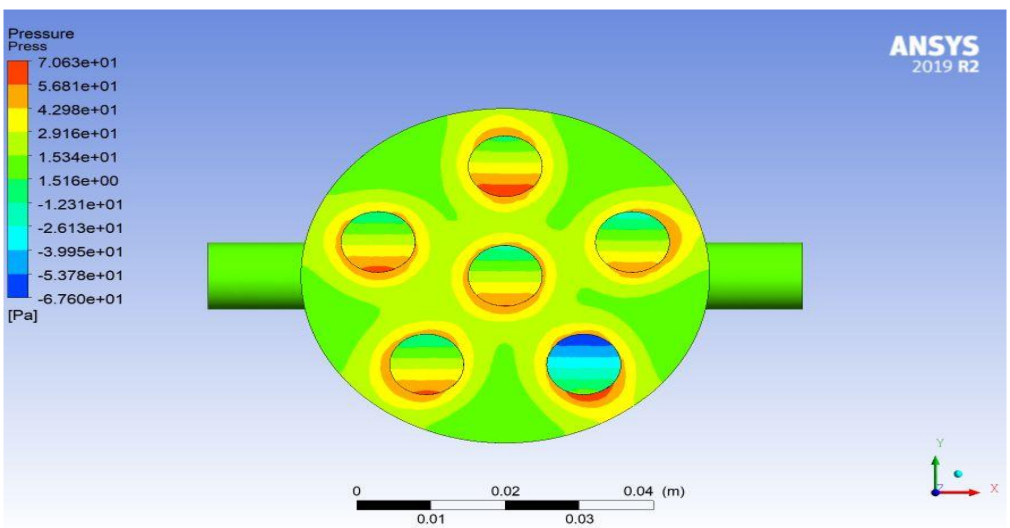


Fig. Pressure contour.

Temperature Distribution

Temperature distribution of cooling system at a same flow rate is shown in Fig. 23. Temperature distribution contour shows, the temperature reduction on the tube side of the cooling system is higher. The shell side have a minimum reduction in temperature.

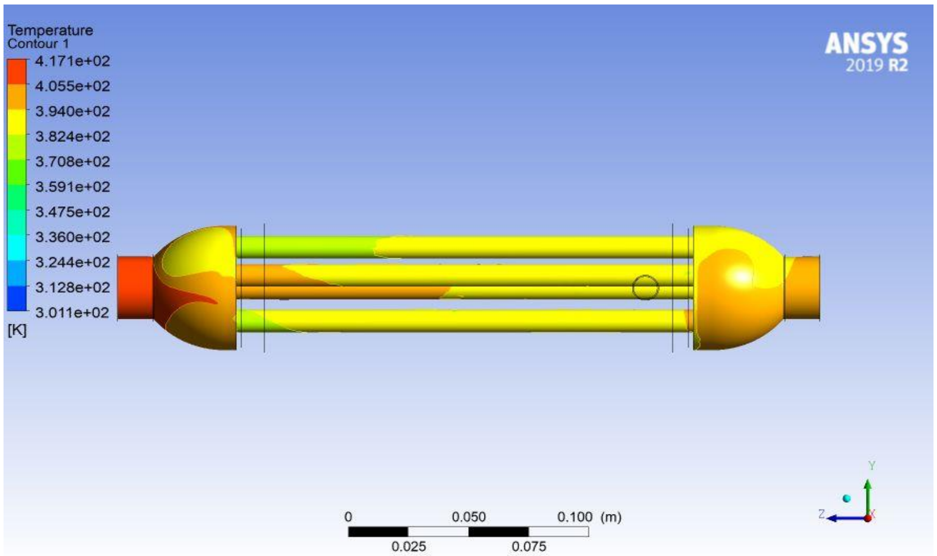


Fig. 23 Temperature contour

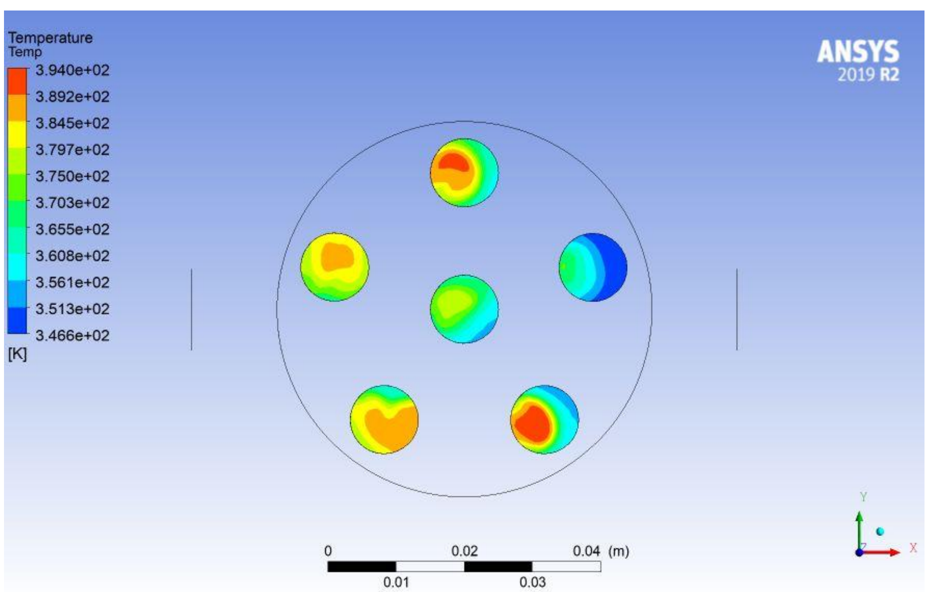


Fig. Pressure contour.

Velocity distribution

Velocity distribution of a cooling system at a same flow rate is shown in Fig. 24. Velocity distribution follows the boundary layer principle and classical hydrodynamic laws. The flow in a smooth pipes EGR cooler is laminar while the turbulent flow exits in a spiral tube.

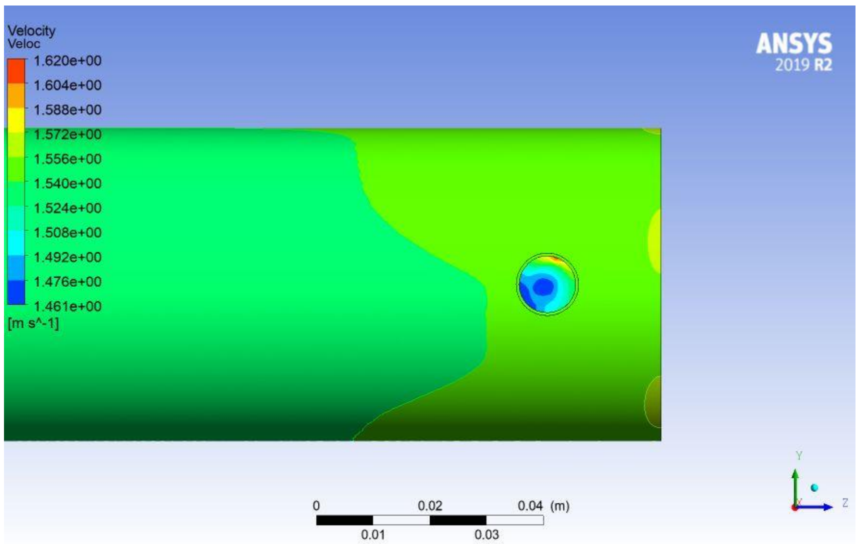


Fig. 25 Velocity contour.

Chapter 6

Conclusion and Future Recommendations

In this study, we have designed and simulate two different types of EGR coolers. Smooth tubes and fully spiral tubes EGR cooler were fabricated and test in the automotive lab of the university. Numerical simulation was performed using a commercial software ANSYS. More compact exhaust gas recirculation cooler could be achieved by decreasing the length of the cooler tubes at a point, where the desired temperature reached.

- 15 Heat transfer efficiency of the EGR cooler with spiral tubes is higher than the EGR cooler with smooth tubes at a same flow rate.
- Overall heat transfer coefficient is higher in spiral tubes than the smooth tubes.
- Pressure drop is more in spiral tubes than in smooth tubes. Fluid flow is turbulent in spiral tubes EGR cooler.
- Heat transfer increases due to the increase in the spiral revolutions and pitch. Increase in depth of the groves also increase heat transfer.
- Fouling deposits decreases the heat transfer efficiency, which can be overcome by increase in the velocity of the exhaust gases and temperature. It can be seen that at higher temperatures NO_x emission becomes constant.
- To increase the heat transfer efficiency, the no of tubes, spiral and pitch can be changed, considering the relation between the efficiency and pressure drop.

There is scope of carrying out further research in relation to this topic.

Reducing the NO_x emission has now become a global challenge, which makes the researchers and engineers to develop the systems that can help to reduce emission. Improving the EGR coolers is one of the factors to reduce the emission. Heat transfer efficiency can be increased by changing the internal structure of the tubes of the cooler and various parameters considering the pressure drop. Fin-plate type EGR cooler can be effective to increase the heat transfer. Employment of different types of wing type vortex generator can also enhance the performance of the cooler. Discrete ribbed and perforated louvered strip type will be the most effective wing type vortex generator in the EGR.

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