Performance Analysis of EGR Cooler for Different Types of Finned Tubes using CFD

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Abstract- **The diesel engine is widely used in modern vehicles. Unfortunately, it is one of the major sources of environmental pollution, since the toxics substances in its exhaust gas, such as oxides of nitrogen (NO_x) and other pollutants, cause adverse health effects. It is well known that decreasing the exhaust gas temperature results in the reductions of NO_x. In order to reduce the high temperature of exhaust gas, a high-efficiency EGR cooler is very suitable. The best way to optimize the heat transfer effect in an EGR cooler is to provide finned surfaces inside the tubes or use corrugations outside the tube surface, thus maximizing the heat transfer from the hotter exhaust gas to the cooler fluid. The focus of the study will be to compare the results with an innovative design of the tubes, with the inclusion of different types of fins inside the tube surface. The entire study will be carried out on CFD and implemented by using ANSYS Fluent 14.5. The main motive of the study will be to utilize the turbulence generators, in our case fins and to get a comparative study with and without them**

Keywords: EGR coolers, fins, corrugations, CFD, ANSYS Fluent.

INTRODUCTION

The Exhaust Gas Recirculation (EGR) Cooler is a liquid to air heat exchanger device that uses engine coolant to reduce exhaust gas temperatures before recirculating them through the engine's intake manifold system. EGR reduces high engine combustion temperature, which adversely affects the formation of Oxides of Nitrogen (NO_x). Before inserting spent exhaust gas into the combustion chamber, its temperature must be reduced, and the EGR Cooler accomplishes this task by reducing as much as 700 degree Fahrenheit from the exhaust gas. In addition to minimizing NO_x levels, EGR system also reduces thermal stress which is developing on cylinder head gaskets and intake/exhaust valves, resulting in longer component life.

The EGR cooler uses engine coolant fluid, and in some cases simple water, for bringing down the exhaust gas temperature. The temperature of exhaust gas which is cooled down by EGR system should be as low as possible to avoid temperature raise. The latest available Technologies are being developed which are focusing on achieving better heat transfer between exhaust gas and engine coolant. Achieving high heat transfer can be done by proper design of diffuser, flow pattern, multi-tubes etc. The tubes used in EGR system are generally straight with smooth surface. However, heat transfer is relatively low. To achieve heat exchanger efficiency, the tube length should be as long as possible. When coolant doesn't flow efficiently inside shell of EGR, the heat transfer in the shell may not occur properly.

Emission regulations are becoming increasingly strict & in order to meet these requirements more efficient and accurate engine models are needed. For lowering down the concentration of oxides of nitrogen in internal combustion engine emission, Exhaust Gas Recirculation (EGR) system can be used. In order to control the NO_x EGR system recirculates a fraction of the exhaust gas back into combustion cylinder which dilutes the incoming air and lowers down the temperature of combustion, thus formation of oxides of nitrogen gets reduced. The NO_x formation is heavily dependent on the combustion temperature; if temperature is high it will react with the oxygen and formed the oxides of nitrogen. In order to inject a small amount of exhaust gas back into inlet manifold of combustion chamber high pressure is needed and this pressure is created by the exhaust gas which is coming out of the exhaust valves and can be controlled with the help of variable turbine blades in the turbo-system, called variable geometry turbine.

EGR is helpful in oxides of nitrogen reduction while limiting the penalties in terms of particulate matter emission and brake specific fuel consumption (BSFC) [6]. The EGR cooler uses water for cooling the exhaust gas. The EGR cooled gas temperature should be as low as possible to avoid formation of oxides of nitrogen. New technologies are being developed for achieving better heat transfer rate between exhaust gas and coolant. This can be achieved by proper design of diffuser, multi-tube, flow pattern etc. The tube used is generally straight and smooth surfaces to avoid any losses. However, heat transfer is relatively low. To achieve high heat exchanger efficiency, the tube length should be as long as possible. When coolant doesn't flow efficiently inside shell of EGR system, the heat transfer in the shell may not occur properly.

The effective shape of diffuser can enhance the heat transfer rate. The function of the diffuser is to distribute hot gasses fluid flow into the tubes and collect cooled gases from output. For better heat transfer prolong shell and tube with multiple shell tube counter flow heat is exchanger is studied.

Diffuser design should make the gas flow into the tubes with equal and as possible as with minimal pressure drop.

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Abbreviations	*Acronyms*
EGR	Exhaust Gas Recirculation
NOx	Nitrogen Oxide
BSFC	Brake specific fuel consumption
CFD	Computational Fluid Dynamics
HC	Hydrocarbon
CO	Carbon Monoxide
PM	Particulate Matter

Theory and Methodology

The entire theory and methodology is based on a single motive which is to attain the maximum temperature drop for the exhaust gases while exiting the EGR so that the reduction of NOx is more prevalent. Thus, the main objective of this study is to optimize the heat transfer rate from the exhaust gases to the coolant that is being used.

Mathematical Formulation

The entire modeling of the EGR cooler is based on a single tube shell tube type heat exchanger. The pipe through which the exhaust gas is passed is of 170 mm in length and having a thickness of 1mm. The pipe has an outer diameter of 32 mm and inner diameter of 30 mm. The inlet and outlet of the exhaust gas are completed by housing having cylindrical cross section. The shell and the tube material are made up of aluminum. The coolant is surpassed into the EGR cooler by means of perpendicular pipe inlets and exits. In our study, water at 323.15 K is taken to be thermal condition of the inlet water. The exhaust gas is initially at a temperature of 739.15 K.

The computational domain here is 3D in nature and energy interactions are maintained between the solid and fluid domains.

Governing Equations:

The conjugate heat transfers and the fluid flow over the Heat Sink structure were numerically modeled. Steady state continuity, momentum (Navier-stokes Equation) and energy equations are solved. Laminar incompressible flow assumed.

Continuity Equation:

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial x}(\rho v) + \frac{\partial}{\partial x}(\rho w) = 0$$

Momentum Equation:

Let (*x*, *y*, *z*) be the orthogonal components of the body force field in the Cartesian coordinate system; then

$$\frac{\partial}{\partial x}(\rho u^2) + \frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial x}(\rho uw) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

$$\frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial x}(\rho v^2) + \frac{\partial}{\partial x}(\rho vw) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + g(\rho - \rho_a)$$

$$\frac{\partial}{\partial x}(\rho uw) + \frac{\partial}{\partial x}(\rho wv) + \frac{\partial}{\partial x}(\rho uw^2) = -\frac{\partial P}{\partial w} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right)$$

***Energy Equation**:*

$$\frac{\partial}{\partial x}(\rho uT) + \frac{\partial}{\partial x}(\rho vT) + \frac{\partial}{\partial x}(\rho wT) = \frac{K}{C_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

Governing Equation of Fin:

$$\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = 0$$

Dimensional number used:

Reynold's number- It is the ratio of inertial forces to the viscous forces. It is used to identify different flow regimes such as Laminar or Turbulent.

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

Nusselt number- The Nusselt number is a dimensionless number that measures the enhancement of heat transfer from a surface that occurs in a real situation compared to the heat transferred if just conduction occurred.

$$\mathrm{Nu} = \frac{\mathrm{h(L)}}{\mathrm{K}}$$

Prandtl number- It is the ratio of momentum diffusivity (viscosity) and thermal diffusivity.

$$\mathrm{P_r} = \frac{\mu \mathrm{C_p}}{\mathrm{K}}$$

Background of Theory

Heat is defined as energy transferred by virtue of temperature difference or gradient. Being a vector quantity, it flows with a negative temperature gradient. In the subject of heat transfer, it is the rate of heat transfer that becomes the prime focus. The transfer process indicates the tendency of a system to proceed towards equilibrium.

There are 3 distinction modes in which heat transfer takes place:

Heat transfer by Conduction:

Conduction is the transfer of heat between 2 bodies or 2 parts of the same body through molecules. This type of heat transfer is governed by Fourier`s Law which states that – "Rate of heat transfer is linearly proportional to the temperature gradient". For 1-D heat conduction,

$$Q = -KA\frac{dT}{dx}$$

Heat transfer by Convection:

When heat transfer takes place between a solid surface and a fluid system in motion, the process is known as Convection. When a temperature difference produces a density difference that results in mass movement, the process is called Free or Natural Convection. When the mass motion of the fluid is carried by an external device like pump, blower or fan, the process is called Forced Convection. In convective heat transfer, Heat flux is given by:

$$Q = hA(T_s - T_a)$$

And third by radiation which is not considered here.

CAD model preparation

A model of single tube shell tube type EGR cooler is made in Ansys Design Modeler. The pipe is having the following dimensions:

Length = 170 mm
Internal Diameter = 10 mm
External Diameter = 12 mm

The shell is having the following dimensions:

Length = 210 mm
Internal Diameter = 30 mm
External Diameter = 32 mm

The entire CAD model is made in such a way that it has the following CAD bodies:

1)Exhaust Gas which is portrayed as a fluid domain.
2)Coolant Domain which is also portrayed as another fluid medium.
3)Outside Shell which is a solid body made of aluminum.
4)Pipe which is another solid body also made of aluminum.
5)Baffle Plates for supporting the pipes also made of aluminum.

The study is based on performance of EGR for three setups of pipes. These are as follows:

1)EGR cooler having simple tube.
2)EGR cooler having internal rectangular fins with breadth and height of the fins being equal and have a value of 2 mm.
3)EGR cooler having internal trapezoidal fins with larger breadth side being 2 mm and smaller breadth side is 1 mm with the height of the fins being 2 mm.

Exhaust gas bodies for the three CAD models have different shapes in total and depends directly on the type of fin that is being used.

Meshing of the CAD model

The meshing of the three CAD models is done in such a way that the skewness for the mesh that is being developed is always less than 0.90 and having good mesh orthogonality quality. Tetrahedral Meshing is performed on all the bodies of the EGR cooler as there are many curved surfaces and moreover the thickness of the pipe as well as the shell body is very less and equal to 1 mm in our case. Moreover, the meshes obtained in all three cases have the following mesh statistics which are given below.

For the CAD model with Plain Tube, the mesh had the following properties

Mesh Count
Nodes = 181173; Elements = 997472
Aspect Ratio
Min = 1.1577; Max = 14.848
Skewness
Min = 2.64184e-07; Max = 0.849065
Orthogonality Quality
Min = 0.175; Max = 0.99774

For the CAD model with Tube having internal rectangular fins, the mesh had the following properties

Mesh Count
Nodes = 181173; Elements = 997472
Aspect Ratio
Min = 1.1578; Max = 14.534
Skewness
Min = 5.4471e-07; Max = 0.849905
Orthogonality Quality
Min = 0.18348; Max = 0.99668

For the CAD model with Tube having internal trapezoidal fins, the mesh had the following properties

Mesh Count
Nodes = 179629; Elements = 987939
Aspect Ratio
Min = 1.1578; Max = 14.534
Skewness
Min = 5.4471e-07; Max = 0.849065
Orthogonality Quality
Min = 0.18348; Max = 0.99711

Boundary conditions

The boundary conditions for the single shell and the tube heat exchanger is as listed in table 1.

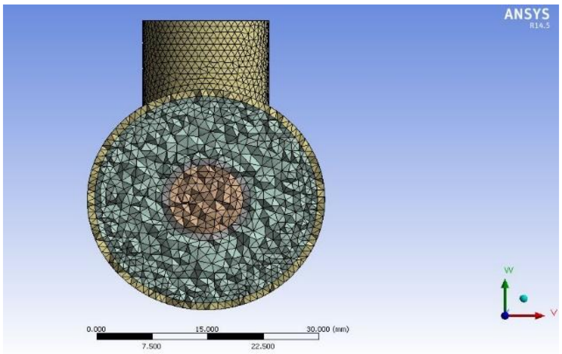
TABLE 1
Boundary Conditions

Parameter	
Inlet Exhaust temperature (K)	739.15
Inlet Water temperature (K)	323.15
Backflow temperature (K)	1000
Exhaust inlet mass flow rate (kg/s)	0.005
Water inlet mass flow rate (kg/s)	0.01
Material Used	Aluminum
Heat transfer coefficient for the outside shell Body	5 W/m^2K

For defining the solid body of the EGR cooler, Aluminium was selected as the desired material which have the following properties: Density-2.7 kg/m^3,Specific heat-0.91 J/kg K,Thermal conductivity-237W/mk.

For defining the coolant in the EGR cooler, Liquid Water was selected as the desired coolant in our case which have the following properties: Density- 998.2 kg/m^3,Specific heat- 4182 J/kg K ,Thermal conductivity-0.6 W/mk.

Further, to define the exhaust gas mixture coming out of the engine through the exhaust, a fluent liquid is created which have the following properties: Density-0.479225 kg/m^3,Specific heat- 1084.36 J/kg K ,Thermal conductivity- 0.0543145 W/mk.



Internal Mesh for EGR cooler without fins

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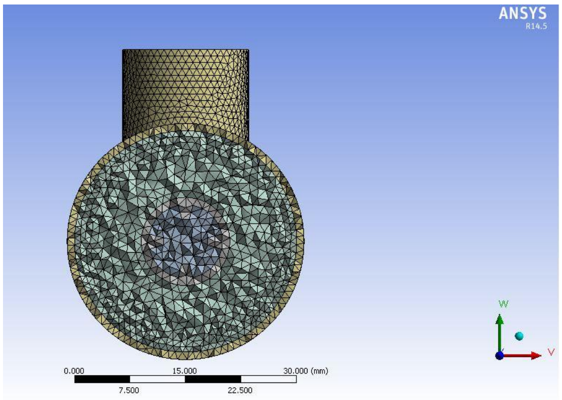
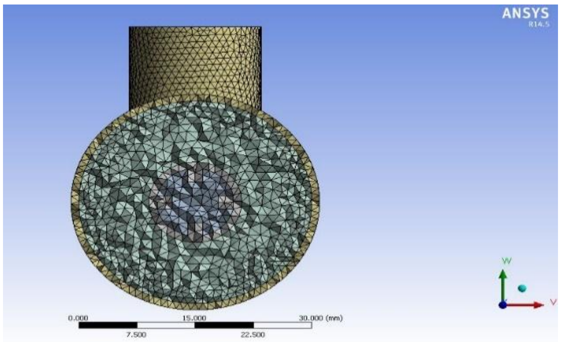


Internal Mesh Section for EGR cooler with trapezoidal fins



Internal Mesh Section for EGR cooler with rectangular fins

RESULTS AND DISCUSSION

This part of the study focuses on the inferences that are gathered from the simulation studies. In this study, our main objective is to maximize the temperature drop of the exhaust gases after passing through the EGR cooler. For gathering this knowledge, on how the three CAD models have performed, depends on the inlet condition of the exhaust and the coolant liquid which are kept the same for the three individual setups. However, we are concentrating on different aspects of the simulation but the most important is how the temperature varies along the length of the EGR cooler.

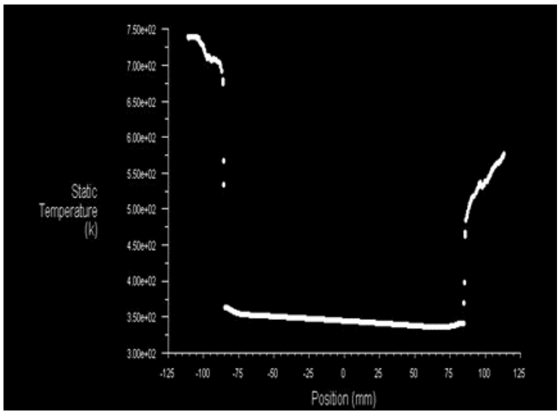
TABLE 2: CFD Results for exhaust temp. of different types of fin tube

Parameter	Model-a	Model-b	Model-c
Outlet exhaust temp. (K)	619.99	548.61	563.02
Temp. Drop	16.12%	25.78%	23.82%

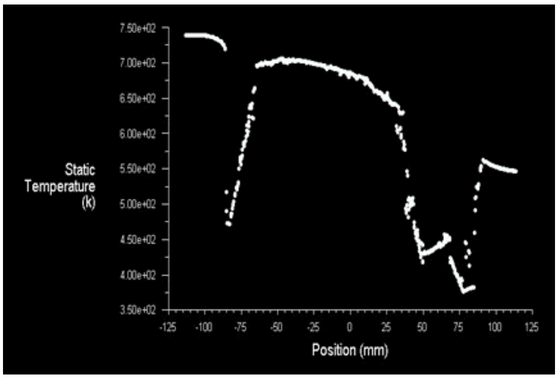
The above table shows the CFD results for different types of EGR cooler. In the above table Model-a represents plain tube, Model-b represents rectangular fin tube and Model-c represents trapezoidal fin tube. Table shows the outlet temprature of the exhaust gas and percentage tmprature drop of different type of EGR cooler when CFD analysis is performed by taking a single tube among all the three type of EGR cooler model.

However, after the entire study is completed via the simulations, it can be concluded that the EGR cooler with rectangular fins showed much better results than both the EGR model with plain tubes and with trapezoidal fins. The exit temperature of the exhaust gases from the EGR cooler with rectangular fins have attained the lowest temperature range and hence it can be concluded that EGR cooler with rectangular fins have the best possible result in reducing the exhaust gas temperature and thereby reducing the formation of NOx from the exhaust gases before getting mixed with the nearby environment completely thus reducing the emission characteristics by many folds.

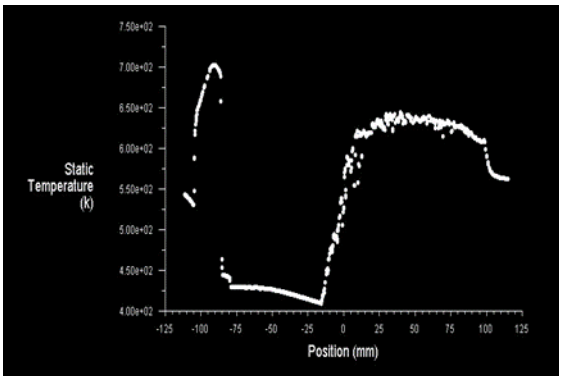
Temperature Variation along a line (parallel to the pipe and almost at the center region



Variation of temperature along a longitudinal axis for EGR cooler without fins



Variation of Temperature along a longitudinal axis for EGR cooler with rectangular fins



Variation of Temperature along a longitudinal axis for EGR cooler with trapezoidal fins

CONCLUSIONS

The conventional methods for testing the performance of a shell and tube EGR cooler are very costly and time consuming. This study shows that CFD analysis technique is very effective in saving time as well as cost associated with the experimental methods of predicting the performance of a proposed design.

The following conclusions can be drawn out based on the different ways to enhance the heat transfer rate from the exhaust gases to the surrounding coolant.

The Maximum Temperature Reduction is seen in case of the EGR cooler with internally placed rectangular fins having the following dimension: Length = 170 mm, breadth = 2 mm and height = 2 mm.

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