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Complex turbulent flow and heat transfer characteristics of tube with different types of internal longitudinal fins in EGR cooler

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***Abstract* - EGR coolers are made up like the shell tube heat exchanger models with the hot exhaust gas being passed through the tubes and the coolant brought into and taken out of the shell chamber. For efficient cooling, several techniques are implemented. However, providing fins of different cross-section areas inside the tubes. In this paper, we will be studying the effects on the flow of the exhaust gas inside the tubes due to a single tube and also the heat transfer that takes place while it interacts with the coolant available in the shell chamber. The focus will be kept on understanding the flow patterns and the heat energy interactions between these fluids. The entire study will be carried 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* - Exhaust gas recirculation (EGR) coolers, fins, corrugations, CFD, ANSYS Fluent 14.5.**

INTRODUCTION

Emission regulations are becoming increasingly strict & in order to meet these requirements, more efficient and accurate engine models are needed. For reducing the concentration of oxides of nitrogen in internal combustion engine emission, Exhaust Gas Recirculation (EGR) system can be used. In order to control the formation of NOx, EGR system recirculates a fraction of the exhaust gas back into the combustion cylinder which dilutes the intake air and brings down the temperature of combustion, thus reducing the formation of oxides of nitrogen. The NOx formation is heavily dependent on the combustion temperature; if the temperature is high it will react with oxygen and form the oxides of nitrogen.
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 as to avoid oxides of nitrogen formation. New technologies are being developed for focusing on 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 [9] 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.

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.

CAD model in Ansys Design Modeler

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 exhaust gas is brought to the system and discharged via cylindrical pipes having internal diameter of 15 mm and external diameter of 18 mm with 10 mm being the length of each of these mouthpieces.

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

1. Model-a, EGR cooler having simple tube
2. Model-b, EGR cooler having internal rectangular fins with breadth and height of the fins being equal and have a value of 2mm
3. Model-c, 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.

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.

The following settings are made for getting a better mesh for the three CAD models:

1. Mesh Type: Tetrahedral
2. Patch Conforming Type
3. Body Sizing for the shell body which is equal to 1 mm.

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

RESULTS AND DISCUSSIONS

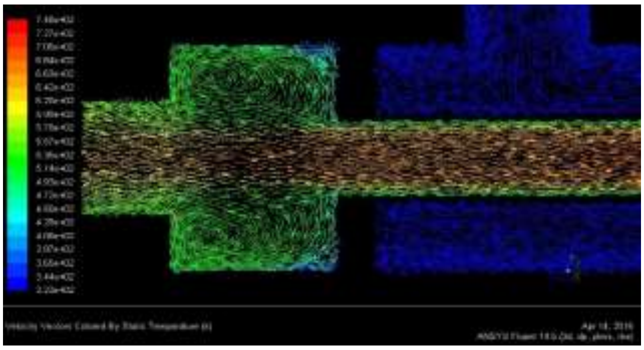
Table 2: CFD Results for exhaust temp. of different types of fin tube

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%**

Table shows the outlet temperature of the exhaust gas and percentage temperature 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.

Velocity Vectorization

This part of the study is based on understanding the behavior of the fluid particles to the diffuser and pipe shapes and also how they react to the energy interactions happening between the coolant and the exhaust gas. For this purpose, we will be entirely focusing on the inlet and outlet region of the pipe in the EGR cooler. This will help us to understand the effect of having a cylindrical diffuser and also how the flow orients itself to the pipes in the way and also out from it.



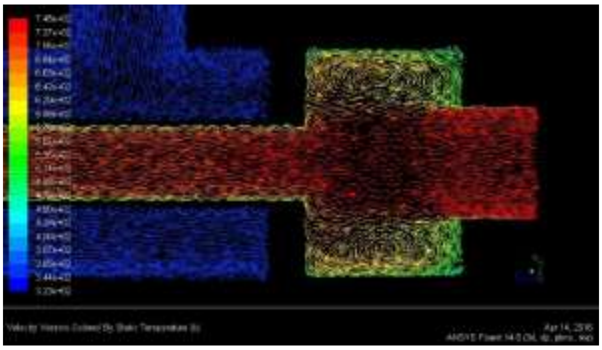


Fig 1: Vector Plot for Temperature in EGR cooler without fins at the outlet section.

Fig 2: Vector Plot for Temperature in EGR cooler Without fins at the inlet section.

From the above velocity vectors for static temperature, it is clearly seen that at the inlet region and at the exit part of the diffuser zones, large eddies are formed due to the flow into the system. Because of these eddies that are being formed, the velocity of the fluid medium at those zones are seen to be abnormally high resulting in low pressure zones and low temperatures zones are developed. This loss of thermal energy is gained by the baffle plate and the walls of the shell near these zones. Thus, the temperatures of the fluid particles away from the pipe entrance and at the two sides of the diffuser causes reduction in temperatures before entering the pipe and results in lesser temperature zones to be created. This is the only reason that the EGR body material and the baffle plate material must be carefully selected as it has to withstand high temperatures without losing their structural balance.
The plots shown in the figure below shows the velocity magnitudes of the fluid particles present at different zones of the EGR cooler and how they react to the temperature interactions between the exhaust gases and the coolant.

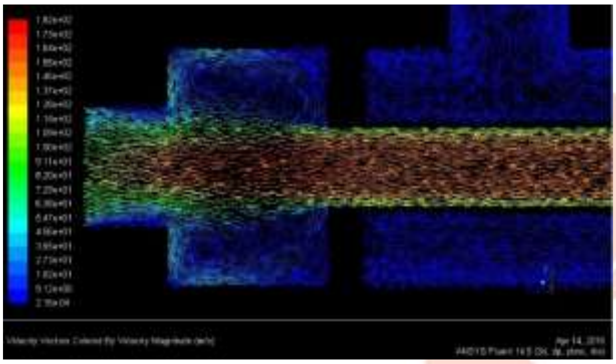


Fig 4: Vector Plots of fluid velocity for EGR cooler without fins at the outlet section

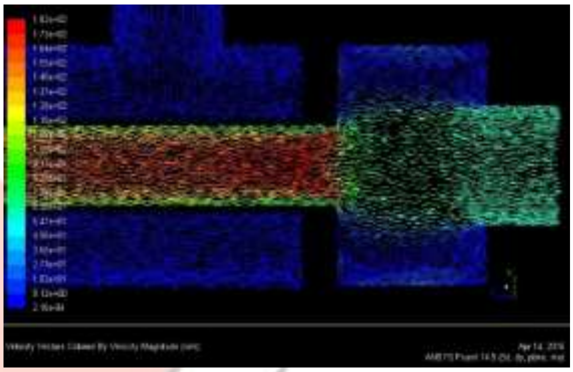


Fig 3: Vector Plots of fluid velocity for EGR cooler without fins at the inlet section

From the above velocity plot, it is very clear that the velocities throughout the fluid domain have variable magnitude zones. The velocity at the inlet to the EGR cooler is less. But it is clearly seen that the velocity at the inlet of the pipe has a maximum value and as the flow in the exhaust gas pipe advances, its temperature decreases and indirectly the velocity drops as the viscosity rises.
From the velocity plot at the exit section of the EGR cooler, it is clearly seen that the velocity vectors show lesser values as compared to those seen at the inlet of the EGR cooler. Similarly, for the velocity vectors on the EGR cooler models with rectangular and trapezoidal fins are clearly shown below:

EGR cooler with rectangular fins

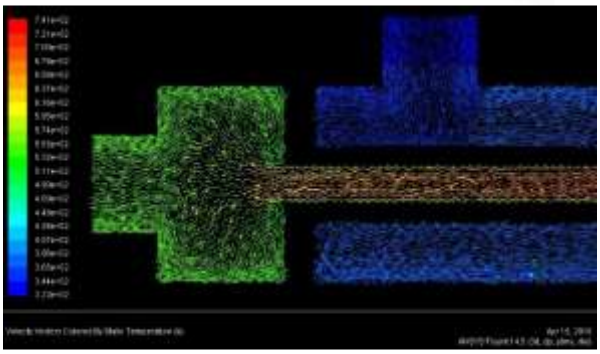


Fig 6: Vector Plot of temperature for EGR cooler cooler with rectangular fins at the outlet section

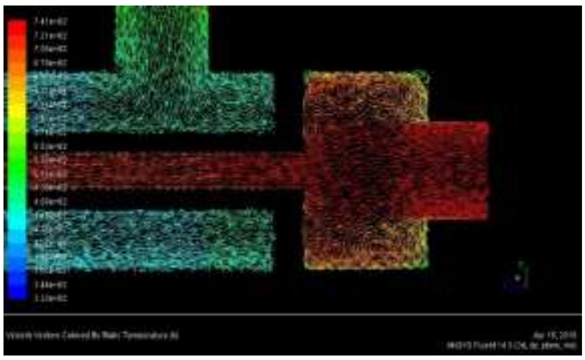


Fig 5: Vector Plot of temperature for EGR cooler with rectangular fins at the inlet section

From the figure above, it is clearly seen that the temperature values inside the pipes fall at a much higher rate when compared to that of the EGR cooler model with plain pipes. However, similar kind of phenomenon is observed in this case also for the two fluid regions seen in the plot above. The temperatures at the diffuser section at the inlet side of the EGR cooler starts decreasing at a much higher rate. Moreover, the coolant section gains much higher values of temperature while exiting from the EGR cooler.

From the vector plot for static temperature at the exit section of the EGR cooler, it is very clear that the temperature of the exhaust gas is lowered by much extent as compared to that of the EGR cooler without fins

From the figure 7 and 8, it can be easily concluded that with respect to the velocities that are attained in the plain tube EGR model, the magnitudes of the velocity at the same positions in the EGR cooler with rectangular fin has much larger values thus implementing that they show much higher rate of heat transfer when compared with that of the plain tube EGR model. The overview is that the more the turbulence that has been created inside the exhaust gas pipes, more is the heat transfer rate. So, in rectangular EGR model it can be concluded that it performs in a much better way than the EGR model with plain pipes.

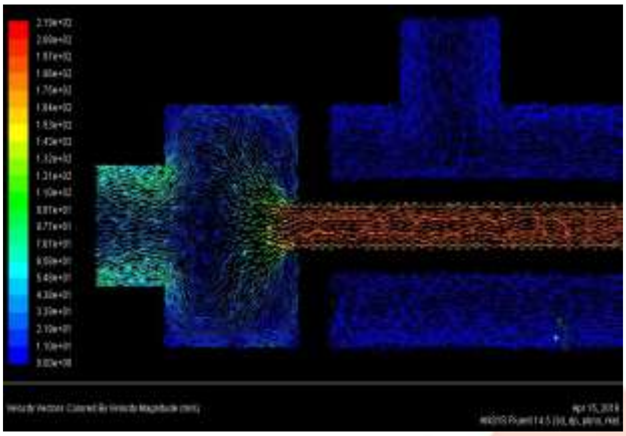


Fig 8: Vector Plot of Fluid velocity for EGR cooler cooler with rectangular fins at the outlet section

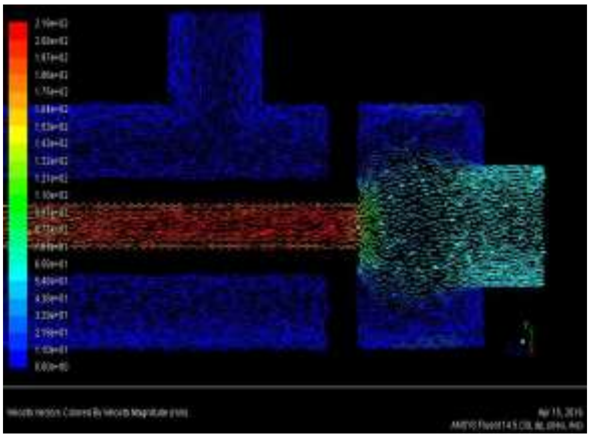


Fig 7: Vector Plot of Fluid velocity for EGR cooler with rectangular fins at the inlet section

EGR cooler with trapezoidal fins

The EGR cooler model with trapezoidal fins have same amount of effect on the exhaust gas temperature reduction as that of the EGR cooler model with rectangular fins however in our study the fins have the following dimension: Rectangular fin: Length = 170 mm, Breadth = 2 mm and Height = 2 mm, Trapezoidal fin: Length = 170 mm, Breadth (smaller side) = 1 mm, Breadth (larger side) = 2 mm and Height = 2 mm.

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.

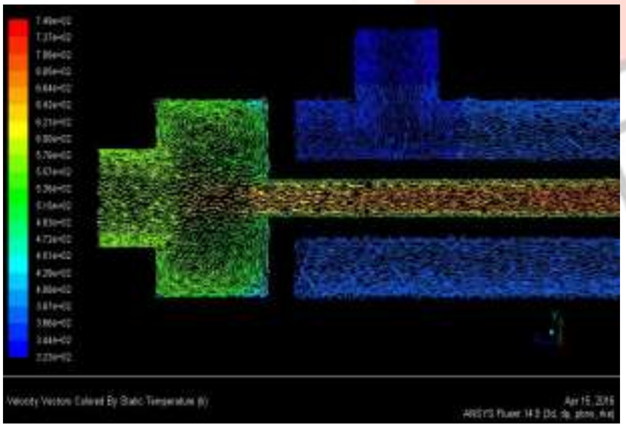


Fig 10: Vector Plots of temperatures for EGR cooler with trapezoidal fins at the outlet section

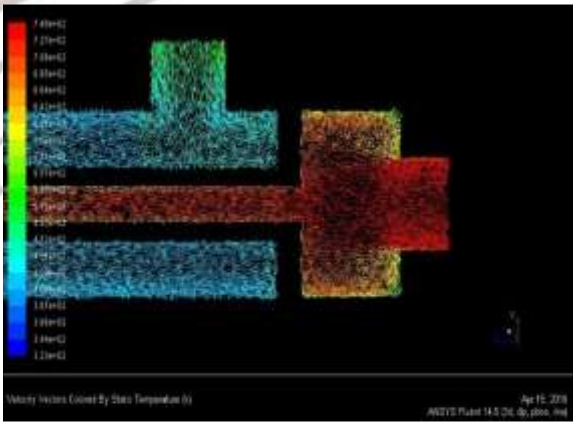


Fig 9: Vector Plots of temperatures for EGR cooler with trapezoidal fins at the inlet section

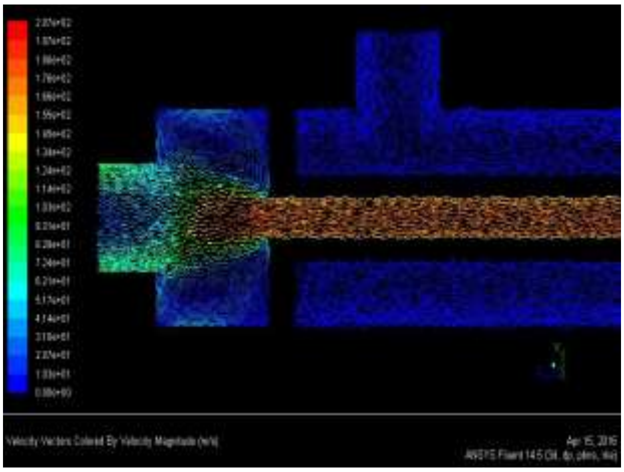


Fig 12: Vector Plot of Fluid velocity for EGR cooler with trapezoidal fins at the outlet section

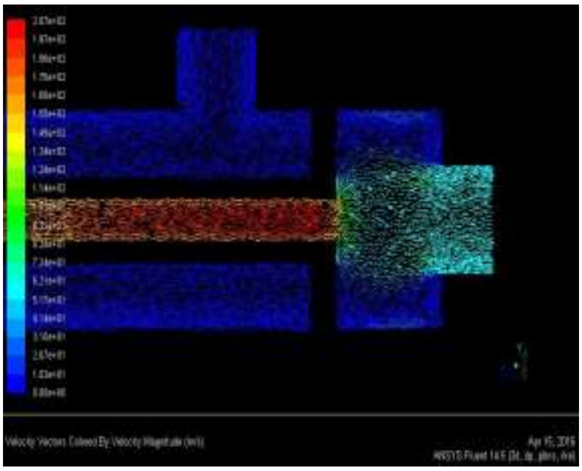


Fig 11: Vector Plot of Fluid velocity for EGR cooler with trapezoidal fins at the inlet section

The above plots showed results having lesser value of temperatures than that of the EGR model with plain pipes. However, 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.

Conclusions

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.

1. 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.
2. Due to presence of fins on the internal surfaces of the pipes in the EGR cooler, a lot of obstruction is seen to develop and there is a lot of temperature variation seen in the case of EGR coolers with fins.
3. The increase in number of tubes will certainly increase the heat transfer rate however due to the effect of gravity on the coolant and the exhaust gas in the pipes, the distribution of energy from the hot gases to the coolant will be different from pipe to pipe.

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