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Experimental and Simulative Performance Analysis of Exhaust Gas Recirculation Cooler By Using CFD

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ABSTRACT
Using energy in an efficient way is very important factor for saving energy and heat exchanger is good example for it. Energy conservation reduces using energy services, which helps to increase environmental quality. EGR cooler follows energy conservation and helps to increase environmental quality by reducing pollution of NOx and other pollutants exhaust from engines. Present experimental study has been carried out to investigate the performance optimization of STHE present in EGR cooler by providing various change in baffles, parameters and temperature to notice the exhaust gas temperature which will suitable to engine, to perform the combustion process. 3-D models of EGR coolers are experimented by using CFD software and the temperature, velocity and pressure zones of fluids in the EGR coolers are simulated and verified by experiments. The thermodynamic performances of the EGR coolers with different changes are analyzed and compared.
Keywords: Shell and Tube Heat Exchanger (STHE), Exhaust Gas Re-circulator (EGR) cooler, (CFD) simulation and verification.

I. INTRODUCTION

An efficient way is very important for saving energy and important aspect for the development of world economy. Heat exchanger is good example for energy conservation i.e. transferring thermal energy between two or more medium. Based on heat exchanger, EGR-cooler is also good example which works on shell and tube heat exchanger and also benefits to reduce pollution.

As, air consists of about 78% of nitrogen, 21% of oxygen and nearly less than 1% of argon, carbon dioxide and other gases. Whereas Highway vehicles, marine engines, locomotives and also aircraft are the sources of pollution in the form of gases and pollutant emissions that affects air quality causing damage to human health. Toxic air pollutants can causes cancer, cardiovascular, respiratory problems and neurological disease [1]. Carbon monoxide (CO) when get inhaled, it affects bloodstream, reduces the availability of required oxygen and extremely harmful to public health. Whereas, an emission of nitrogen dioxide (NO2) from transportation sources reduces lung function, affects the respiratory immune defense system and increases the risk of respiratory problems.

In diesel engines, it is highly necessary to reduce the amount of NOx in the exhaust gas, which causes environmental issues like acid rain etc. India is the fourth largest energy consumer in the world, per capita consumption of diesel. Around 50,000 diesel taxis runs on Delhi roads on average day, burns around 10 lakh litres of diesel. The ban on diesel vehicles will throw the lives of so many families out of gear. Also, add to that another 5.2 lakh private diesel cars also runs which increase the scale of the issue noticeable. Delhi is the most polluted city in the world according to multiple surveys from the World Health Organization (WHO) to the Indian Institutes of Technology in Delhi, Mumbai and Kanpur. Also, Diesel emissions are the worst among all vehicular pollutants which have high levels of deadly particles and nitrogen dioxide compared to Petrol engines [2]. So, it is very important to follow Indian emission standards [3] related to Euro standards to control pollution due to transportation and one efficient way for ensuring this is by providing Exhaust Gas Re-circulation (EGR) system.

Figure 1 shows Exhaust Gas Recirculation system; it means it uses exhaust gases for process i.e. recirculates gas which is composed of NOx and PM (Particulate matter). Whereas, the exhaust gas acts as an inert gas in the combustion chamber and it does not participate in the combustion reaction. Due to this, it leads to a decrease in the combustion temperature by different effects. In between this, the fuel molecule needs more time to find an oxygen molecule to react with, as there are inert molecules around it [5]. This slows down the combustion speed and thus reduces the peak combustion temperature inside chamber, as the same amount of energy is released over a longer period of time. Therefore, in order to reduce NOx emissions in the exhaust, it is very necessary to keep the peak combustion temperature inside chamber under control. As formation of NOx don't occur at temperatures below 1300°C to 1600°C i.e. before 1726.85°C [6].

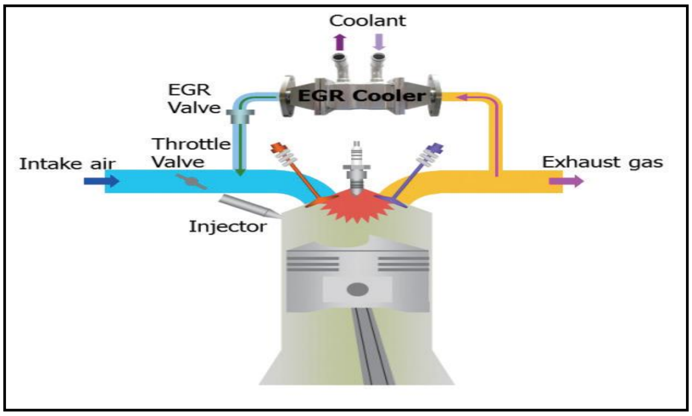

Fig.1 EGR cooler system [4]

Reduction of cylinder temperatures can be achieved in three ways.

- By enriching the air fuel (A/F) mixture.
- By lowering the compression ratio and retarding ignition timing.
- By reducing the amount of Oxygen in the cylinder.

By enriching the air fuel (A/F) mixture ratio, it can be used to reduce combustion temperatures. However, this increases HC and carbon monoxide (CO) emissions. Whereas, lowering the compression ratio and also retarding ignition timing makes the combustion process to start at a less than the optimum point and causes reduction in the efficiency of combustion.

These two technique ways lowers the cylinder temperature and reduces formation of NOx, but it also reduces fuel economy and performance causes creation of excess soot, which leads to more frequent oil changes.

So, the best way is reducing the amount of Oxygen in the cylinder. By reducing oxygen amount in cylinder combustion process which helps in lowering cylinder temperature. This is done by circulating some exhaust gas and it mix with the engine inlet air. This process is known as Exhaust Gas Recirculation.

II. EXPERIMENTAL DETAILS

The STHE of counter flow is use in EGR cooler. The square style uses more of a "radiator" style of channels and fins. The round style uses a tube-type heat exchanger and features of tubes running from end-to-end. Whereas, the round style with its tube-type heat exchanger is a much more reliable type of heat exchanger than square type cooler. The good thing about round style is when things get hot; they all expand in the same direction and at the same rate. When things cool down, they contract in the same direction at the same rate, too. This leads to reduced thermal stress throughout the structure.

Most of the EGR coolers are shell and tube type heat exchangers (STHEs) into which the Gas flows inside tube side and Coolant flows at shell side.

2.1 Computational model for EGR cooler

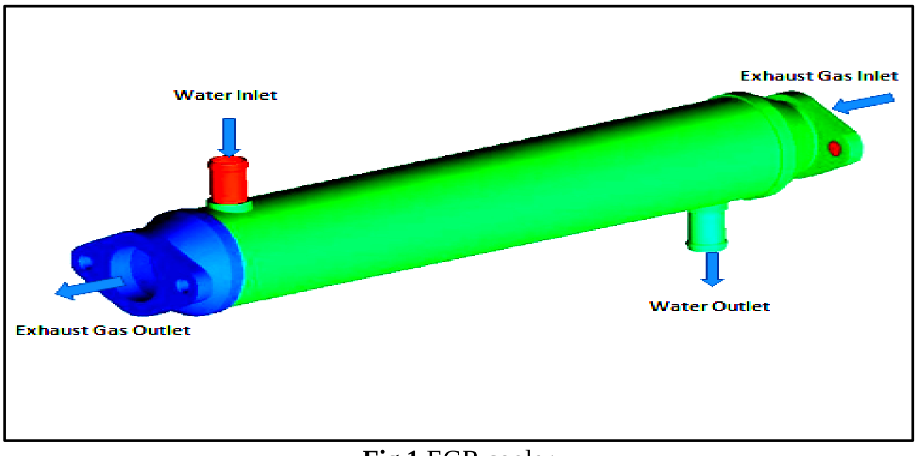

Fig.1 EGR cooler

Geometric model is created in Pro-E wildfire 5 and validated in star ccm+. As shown in figure 2, the seven tube egr cooler is modeled as a baseline without baffle plates. Whereas, baffle plates was added to baseline to create variant 1, which shows four baffle plates in figure 3.

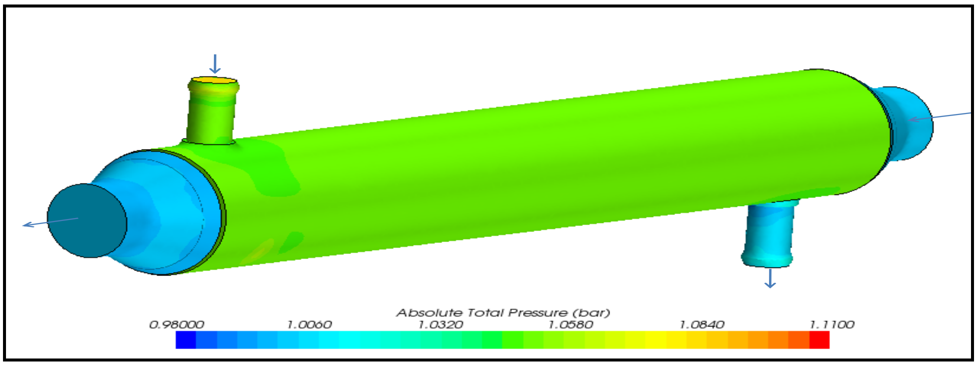

Fig.2 Baseline

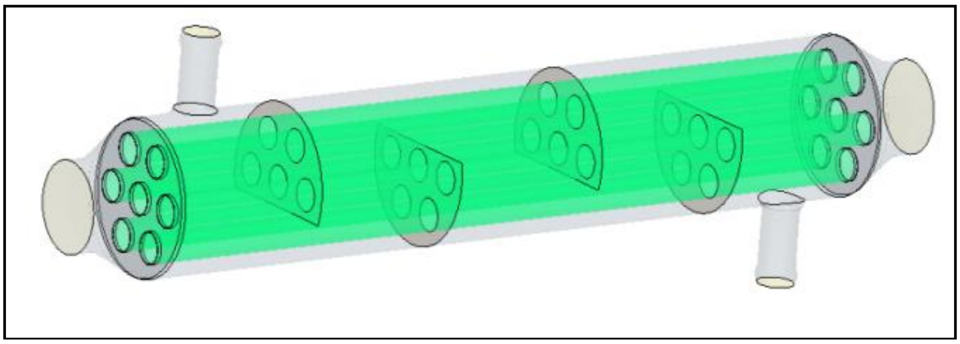

Fig.3 Variant 01

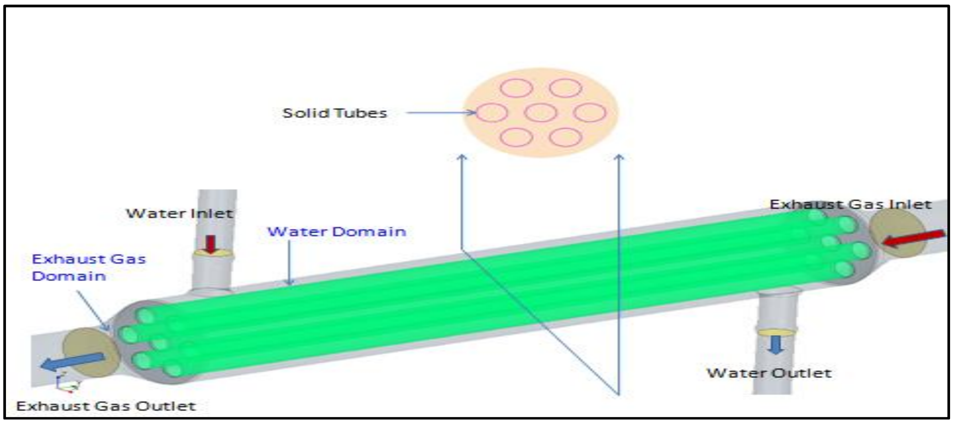

Fig.4 Domain in STHE of EGR

Computational fluid dynamic software is used for determining the flow patterns inside shell and tube, temperature distribution at various points of shell and tube. The Star ccm+ is used for numerical simulation of egr cooler. Geometric model was imported into star ccm + and post processed by applying meshing and simulated with required parameters. The shell and tube heat exchanger is divided into three regions Air domain, Water domain and Solid domain. The meshing is done using polyhedral mesh for the fluid domain and with embedded-thin mesh for the solid region. Total mesh count is around 1 million (1000927) cells.

2.2 Dimension detail of EGR cooler

All dimensions are in mm (millimeter). Single segmental type of baffle plate is used in this design. The Egr contains various diameter dimensions at various points in design. So, the dimensions mentioned are in terms of (l x b x h) in below table.

Table 1: Dimension of EGR cooler

No	Part Name	Quantity	Dimension (l x b x h)
1	Inlet-header	1	35 x 50 x 46
2	Outlet-header	1	35 x 50 x 46
3	Plate	2	1.5 x 54 x 54
4	Baffle plates	4	1 X 54 x 25.50
5	Tubes	7	304 x 10.62 x 10.62
6	Shell	1	301 x 54 x 54
7	Shell-Inlet	1	25 x 15.5 x 15.5
8	Shell-Outlet	1	25 x 15.5 x 15.5

A four baffle plate Egr cooler is to be considered for the experimental validation purpose. We have manufactured four baffle plate Egr cooler and carried experiments on it. The Steel of grade SS-306 is used in the tube material and Aluminium 24 is used as shell material in this case for manufacturing purpose.

2.3 Material properties

A four baffle plate Egr cooler is to be considered for the experimental validation purpose. We have manufactured four baffle plate Egr cooler and carried experiments on it. For experiment purpose, following material were selected for shell and tube respectively. These parameters are carried out in Star ccm+ which acts as solver, and parameters to be considered with their different properties which are as follows.

Table 2: Material properties

	Tube material	Shell material
Material	Steel of grade SS-306	Aluminium 24
Specific heat (Cp)	460 J/Kg-K	963 J/Kg-K
Thermal conductivity	25 W/m-K	96.3 W/m-K
Density (ρ)	7700 Kg/m3	2790 Kg/m3

Coolers are mainly consisted of welded stainless-steel sheet metal and so the production costs have been comparatively costly compare to aluminum. Another advantage of aluminum is its much higher thermal conductivity versus steel. A comparison: stainless steel has a conductivity of 14.7 W/m·K (Watt per meter and Kelvin) whereas Die-cast aluminum has around 180 W/m·K, more than twelve times as much. Aluminum's excellent heat conductivity makes it possible to achieve a very high cooling performance even under relatively cramped conditions.

2.4 Experimental set up of EGR cooler model for validation

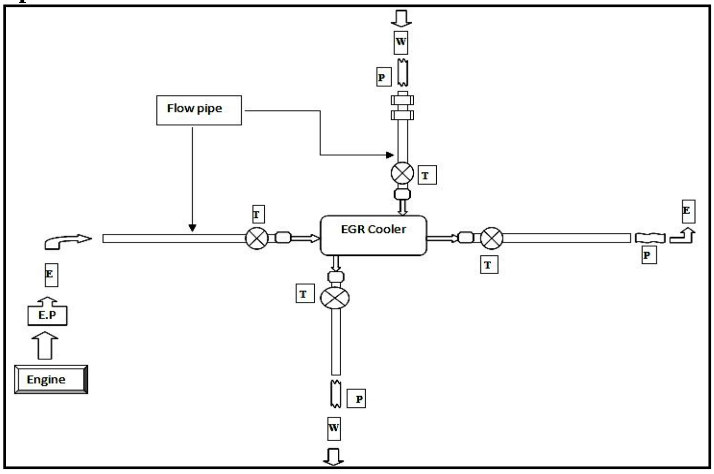

Fig.5: Schematic Diagram of set-up

For experimental validation purpose, we provided all required accessories as per above diagram:

T = Temperature sensor, i.e. Thermocouple with indicators, P = Hose pipe, E = Exhaust gas, W = Water (coolant), E.P = Exhaust gas outlet pipe.

Fig.6: Experimental Validation Set-up

In above diagram, Egr cooler is attached to exhaust manifold of a vehicle whose engine is in running condition (approx above 2100rpm). As, It is experimental study, egr cooler was attached to silencer part of the exhaust manifold. The initial boundary condition provided at the start of experiment to the egr cooler is as follows

Parameter	Mass flow [kg/s]
Exhaust gas inlet mass flow rate	0.00694
Water Inlet mass flow rate	0.3333

By providing above mention inlet boundary condition, the experiment was carried out at different stages of temperature. In this way, the experiment is carried out under technical expert guidance and output results obtained.

III. RESULT AND DISCUSSION

The numerical study and experimental validated study is carried out on four baffle plate egr cooler as per experimental setup. The comparison between experimental validated result and corresponding numerical simulations results are presented for the four baffle plate egr cooler and the error percentage for the same is calculated for verification purpose.

3.1 Experimental Validation Results

The following results were obtained in experimental validation study. Experiment was carried out at different stages of temperature to observe the difference in exhaust gas output result.

No.	Exhaust Gas Inlet Temperature ºC	Coolant Inlet Temperature (Water) ºC	Exhaust Gas Outlet Temperature ºC
1	231	36	135
2	233	39	139
3	235	41	144

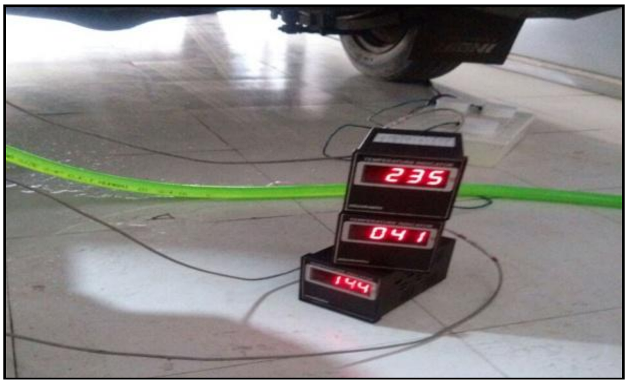

Fig.1 (a): Experimental Validation (235ºC)

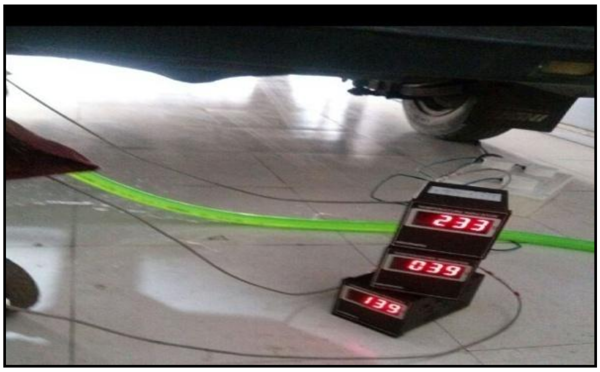

Fig.1 (b): Experimental Validation (233ºC)

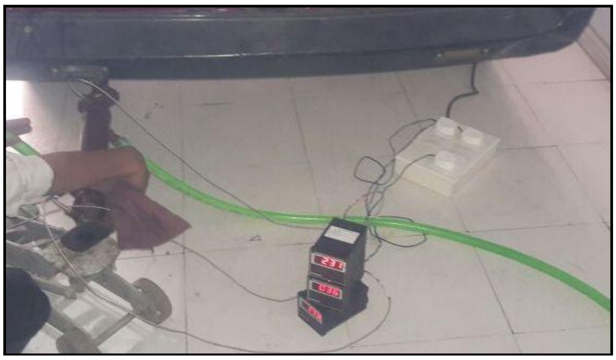
Fig.1 (c): Experimental Validation (231ºC)

3.2 CFD Results

The obtained validation results need to be verified by CFD results. For this reason, cfd simulation of obtained experimental validation results was carried out. For this star ccm+ was used for cfd simulation of four baffle plate EGR cooler with obtained experimental validation result. Required properties of exhaust gas and water as per temperature in cfd software was provided and obtained output results as follows.

No.	Exhaust Gas Inlet Temperature ºC	Coolant Inlet Temperature (Water) ºC	Exhaust Gas Outlet Temperature ºC
1	231	36	122.55
2	233	39	125.13
3	235	41	127.12

Figure 2 (a) shows the temperature distributions inside the egr cooler with four baffles at 235ºC. Exhaust Gas Outlet Temperature of 127.12ºC was obtained. It required nearly 500 iterations. A minimum and maximum value of temperature distributions is 80 ºC and 270ºC respectively.

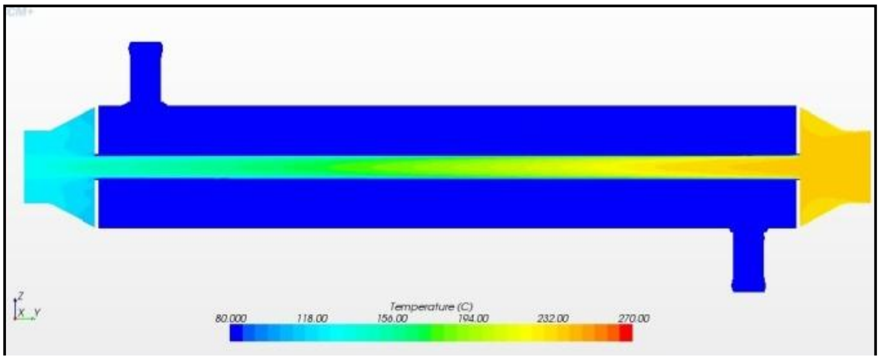

Fig.2 (a): Temperature plot (235ºC)

Figure 2 (b) shows the velocity distributions inside the egr cooler with four baffles at 235ºC for fluid flow of water. A minimum and maximum value of velocity distributions is 0 m/s and 1 m/s respectively.

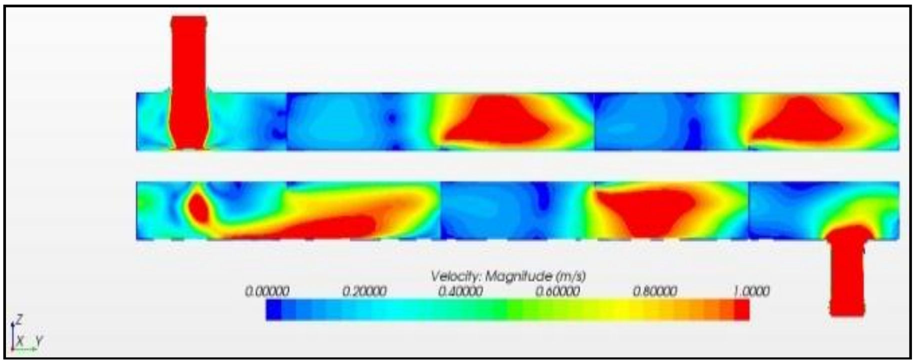

Fig.2 (b): Velocity plot (235ºC)

Figure 3 (a) shows the temperature distributions inside the egr cooler with four baffles at 233ºC. Exhaust Gas Outlet Temperature of 125.13ºC was obtained. It required nearly 470 iterations. A minimum and maximum value of temperature distributions is 80 ºC and 270ºC respectively.

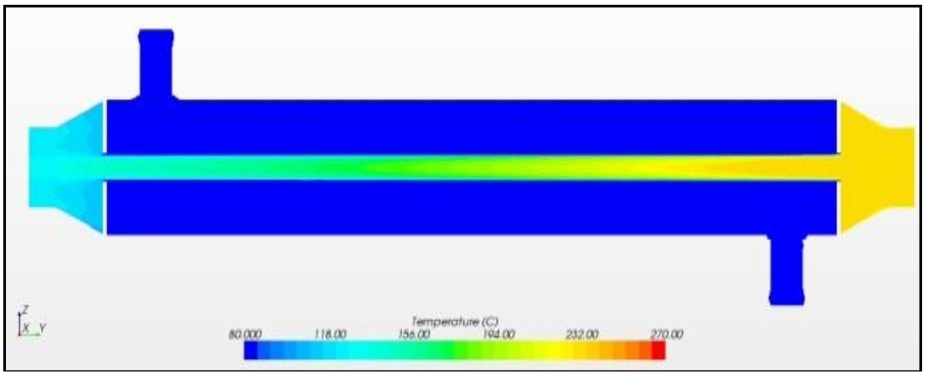

Fig.3 (a): Temperature plot (233ºC)

Figure 3 (b) shows the velocity distributions inside the egr cooler with four baffles at 235ºC for fluid flow of water. A minimum and maximum value of velocity distributions is 0 m/s and 1 m/s respectively.

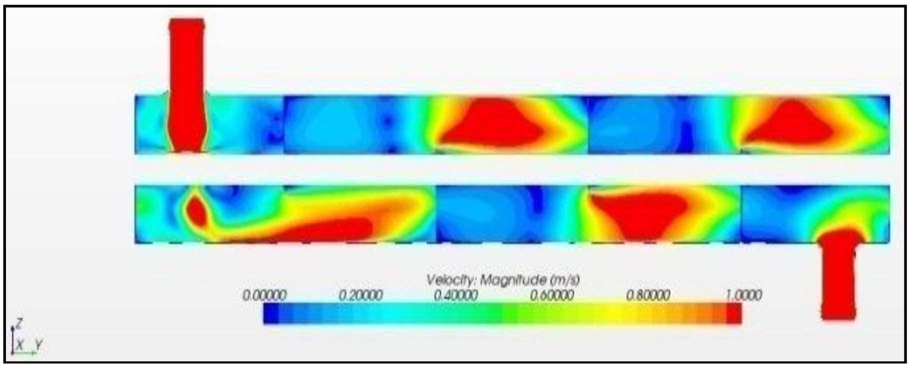

Fig.3 (b): Velocity plot (233ºC)

Figure 4 (a) shows the temperature distributions inside the egr cooler with four baffles at 231ºC. Exhaust Gas Outlet Temperature of 122.55ºC was obtained. It required nearly 470 iterations. A minimum and maximum value of temperature distributions is 80 ºC and 270 ºC respectively.

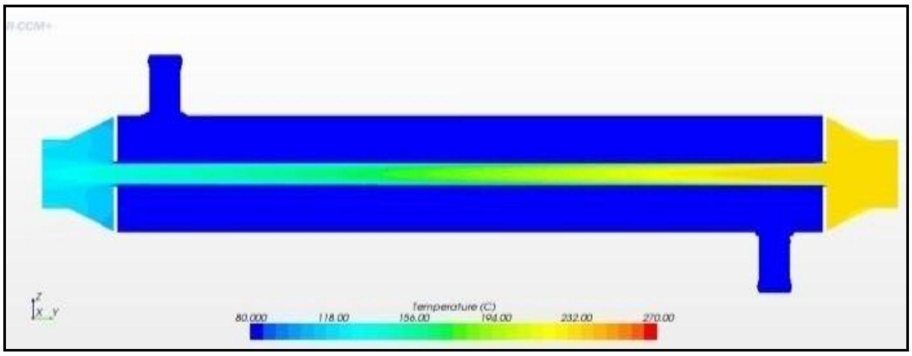

Fig.4 (a): Temperature plot (231 ºC)

Figure 4 (b) shows the velocity distributions inside the egr cooler with four baffles at 235ºC for fluid flow of water. A minimum and maximum value of velocity distributions is 0 m/s and 1 m/s respectively.

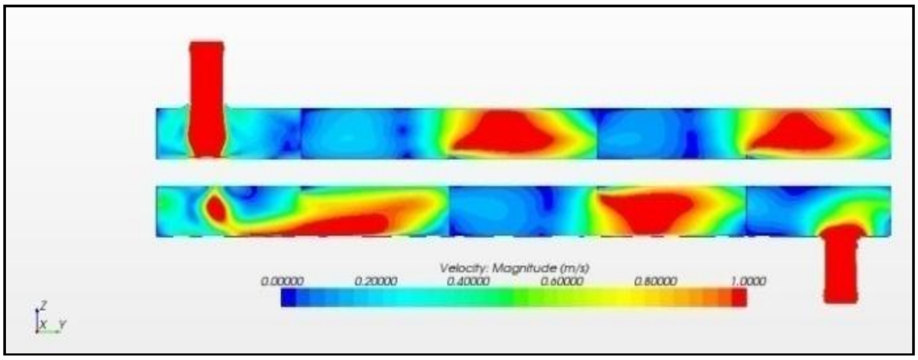

Fig.4 (b): Velocity plot (231 ºC)

The following graph is plotted based on the above obtained experimental validation result and CFD result. The graph itself shows that both results follow the same pathway with obtained difference in temperature. The graph is in between exhaust gas inlet temperature provided and obtained exhaust gas outlet temperature in CFD as well in experimental validation study.

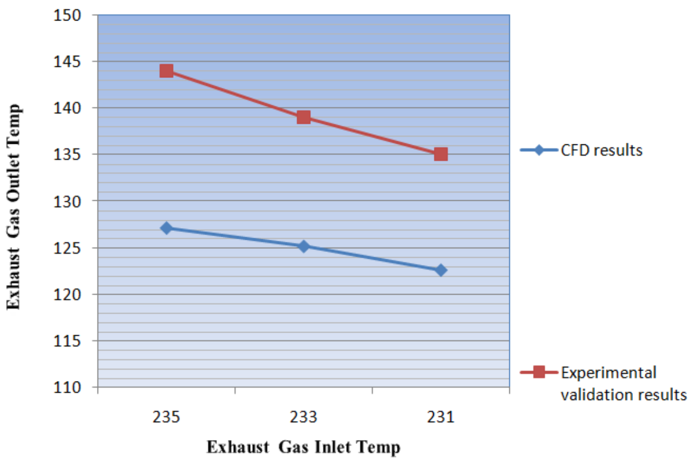

Fig.5: Exhaust Gas Inlet Vs Exhaust Gas Outlet temperature (ºC)

3.3 Error Percentage

The Experimental exhaust gas outlet temperature results found to be nearby to CFD exhaust gas outlet results as shown in figure 5 with around 89.6923 % accuracy.

Case	% Error = { (Experimental - CFD)/Experimental} *100
I	9.2222
II	9.9784
III	11.7222
Absolute Average Error	**10.3076%**

% Error = (Experimental - CFD)/Experimental *100

Case - I
Experimental exhaust gas outlet temperature = 135
CFD exhaust gas outlet temperature = 122.55
%Error={(Experimental- CFD)/Experimental}*100
= {(135-122.55)/135} * 100
= 9.2222 %

Case - II
Experimental exhaust gas outlet temperature = 139
CFD exhaust gas outlet temperature = 125.13

%Error={(Experimental- CFD)/Experimental}*100
= {(139-125.13)/139} * 100
= 9.9784 %

Case – III
Experimental exhaust gas outlet temperature = 144
CFD exhaust gas outlet temperature = 127.12

%Error={(Experimental- CFD)/Experimental}*100
= {(144-127.12)/144} * 100
= 11.7222 %

Absolute Average Error = Case (I+II+III)/3
= (9.2222 + 9.9784 + 11.7222)/3
= 10.3076 %

Accuracy = (100 – Absolute Average Error)
= (100 – 10.3076)
= **89.6923 %**

In this way, the experiment for four baffle plate EGR cooler is carried out. An experimental gas outlet validation result shows a good agreement with the CFD exhaust gas outlet results, with around 89.6923 % accuracy approximately 90 % i.e. approximately 10% error only, which shows it as a good acceptable result.

To satisfy above objectives following is the scope of this work:

1 Design is made in Pro-E 5 wildfire.
2 Star ccm+ is provided for meshing.
3 For providing simulation with condition Star ccm+ is used which acts as a solver for this geometry.
4 The simulation is done on different level with different condition.
5 Data is analysed.
6 In future stage, By changing design of Egr cooler, changing tube design or number of tubes, changing type of coolant, changing number of various shell inlet or outlet, changing length of Egr or change in area of Egr, We can achieve better performance.
7 Also, Design of Egr cooler can be study upon different engines like heavy duty diesel engine or LPG fueled diesel engine, also with different fuels eg. Bio-Diesel with Jatropha, Hydrogen as dual fuel,

IV. CONCLUSION

It is seen that by adding number of baffles in STHE of EGR, the exhaust gas temperature decreases.

1 It is seen that by decreasing water inlet temperature to STHE of EGR, the exhaust gas temperature decreases.
2 So, as on decreasing water (coolant) inlet temperature to STHE of EGR, the exhaust gas temperature decreases as per common ratio, as shown in graph.
3 We achieve desired temperature which suits to engine combustion reaction and keeps engine in healthy condition.
4 We also experimentally validated performance of egr cooler and compared with cfd results for verification, which shows a good acceptable result.

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