Modeling and CFD Simulation of Exhaust Gas Recirculation Cooler for Diesel Engine and Compare It with Triangular and Square Fin Tube EGR

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Abstract— The exhaust gas recirculation (EGR) is a process for minimizing the nitrogen oxide (NOx) emissions from the exhaust of the IC engine. Our main aim is to develop a design of EGR Cooler for BS IV diesel engine which reduces the NOx percentage in the exhaust gas. EGR recirculation about small part of the exhaust gases back into the inlet of the cylinder where it merges with the fresh air and due to which it reduces the part of Oxygen. It reduces the Oxygen concentration due to chemical reaction and dilutes the intake charge, due to which it also reduces the temperature inside the cylinder which will simultaneously reduce the NOx percentage due to reducing the formation of NOx.. When we recycle about 20% of exhaust gas will reduce NOx emission about 87%. Therefore we make three different models A, B, C. Model-A is simple shell and tube type, which has simple tube. In model-B we replaced simple tubes by externally triangular finned type circular tube because it increases the heat transfer rate and therefore we get increased effectiveness of the cooler. And in the Model-C, we replace the plane tube in same model by square finned tube. Now we compare all the three models by their effectiveness, and on the basis of comparison suggest using most effective Model among them. Mainly the comparisons were made between shell & finned tube EGR cooler and on the basis of comparison we prefer the model which has high effectiveness than the other.

Key words: Exhaust gas recirculation (EGR), Nitrogen Oxides (NOx), Oxygen (O2), Mass of Exhaust Gas Recirculation (MEGR)

I. Introduction

Exhaust gas recirculation (EGR) may be a Nox emission removal technique applicable to a large number of diesel engines. The configuration of the EGR system depends on the desired EGR rate and alternative demands of the actual application. Nox within the ICE exhaust gas is closely associated with the critical cycle temperature and accessible quantity of oxygen within the combustion chamber, therefore Nox emissions from diesel engines will be reduced by reducing the critical temperatures of combustion. At the present to cut back peak combustion temperature we have a tendency to use EGR. The EGR system reduces Nox production by re-circulating little amounts of exhaust gases into the manifold wherever it mixes with the incoming air/fuel charge.

By diluting the air/fuel mixture below these conditions, peak temperature and pressure are reduced, resulting in an overall reduction of NOx output. Diesel engines are assumed as a decent option to petrol engines as a result of the exhaust lower quantity of emissions. On the opposite hand, higher emissions of oxides of nitrogen (NOx) and particulate matter (PM) are detected as major issues. though major constituents of diesel exhaust contain carbon dioxide (CO2), water vapor (H2O), nitrogen (N2), and oxygen (O2); carbon mono oxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and particulate matter (PM) are exists in smaller amount bit are environmentally important qualities.

Better fuel economy and better power with lower maintenance value has enhanced the recognition of internal-combustion engine vehicles. Diesel engines are used for bulk movement of product, powering stationary/mobile devices, and to generate electricity additional economically than any alternative device during this size limits. In most of the world automotive markets, record diesel automotive sales are discovered in recent years. The exhorting anticipation of extra enhancements in fuel and diesel vehicle sales in future have forced diesel engine makers to upgrade the technology in terms of power, fuel economy and emissions.

In recent year due to globalization and industrial development, transportation industries are flourishing rapidly. Such industries are considerably answerable for atmospherically pollution that is harmful to human health and atmosphere. Combustion engines are main power hub for the automobile vehicles that is used by transportation industries. Eventually all the diesel engines have high thermal efficiencies due to their high compression ratio and lean air-fuel operation. The high compression ratio produces the high temperatures needed to realize machine ignition and the ensuing high expansion ratio makes the engine discharge less thermal energy in the exhaust. Due to lean air -fuel mixture, additional gas in the cylinders is existing to facilitate complete combustion. Increasing diesel consumption will increase the un-burnt gases that pollute the surrounding air. Therefore sensible efforts are being made to cut back the pollutants emitted from the system without loss of power and fuel consumption. Recent concern over development in technology is that the low environmental impact. In fact, partial recirculation of exhaust gas, that is not a new technique, has recently become essential, together with alternative techniques for attaining lower emission levels. The development of a brand new generation of exhaust gas recirculation (EGR) valves and enhancements in electronic controls permit a stronger EGR accuracy and shorter reaction time in transient condition. Pollutants are as a result of of the incomplete burning of the air-fuel mixture in the combustion chamber. The most important pollutants emitted from the exhaust attributable to incomplete combustion are-

1) Carbon monoxide (CO)
2) Hydrocarbons (HC)

3) Oxides of nitrogen (NOx)

If, combustion is complete, the only substance being expelled from exhaust would be water vapor that is harmless, and carbon dioxide, that is an inert gas and, intrinsically it's in some way harmful to humans.

II. Mechanism of Formation of (NOx)

Oxides of nitrogen is made in very little quantities will cause pollution. Whereas prolonged exposure of oxides of nitrogen is dangerous to health. Oxides of nitrogen that occurs solely within the engine exhaust are a mixture of nitric oxide (NO) and nitrogen dioxide (NO2). Nitrogen and oxygen react at comparatively higher temperature. Nox is made within the combustion chamber in post-flame combustion method within the hot temperature region. The high peak combustion temperature and abundance of oxygen are the main reasons for the formation of Nox. In the existence of oxygen within the combustion chamber at high combustion temperatures the subsequent chemical reactions can takes place behind the flame.

$$N_2+O_2 = 2NO$$

$$N_2+2H_2O = 2NO+H_2$$

Calculation of chemical equilibrium shows that a significant amount of NO will be formed at the end of combustion. The majority of NO formed will however decompose at the low temperatures of exhaust. But, due to very low reaction rate at the exhaust temperature, a part of NO formed remains in exhaust. The NO formation will be less in rich mixtures than in lean mixtures. The concentration of oxides of nitrogen in the exhaust is closely related peak combustion temperature inside the combustion chamber.

III. Exhaust Gas Recirculation

Exhaust Gas Recirculation is a good technique of Nox management. The exhaust gases principally carries with it carbon dioxide, nitrogen etc. and the mixture has higher specific heat compared to surrounding air. Re-circulated exhaust gas displaces intake air getting into the combustion chamber with carbon dioxide and water vapor that exists in engine exhaust. As a consequence of this air displacement, lower quantity of oxygen in the intake mixture is present for combustion. Reduced oxygen present for combustion lowers the effective air–fuel ratio. This effective reduction in air–fuel ratio affects exhaust emissions considerably. Additionally to this, combination of exhaust gases with intake air will increase specific heat of intake mixture that results in the reduction of flame temperature. So combination of lower oxygen amount within the intake air and reduced flame temperature reduces rate of Nox formation reactions. The EGR (%) is outlined because the mass % of the recirculated exhaust (MEGR) within the total intake mixture (Min).

$$EGR\ (\%) = (MEGR / Min) \times 100$$

From above three methods, EGR is the most economical and broadly used system to manage the formation of oxides of nitrogen within the combustion chamber of I.C. engine. The exhaust gas for recirculation is taken through a passageway and versed management valves for regulation of the amount of recirculation.

IV. Engine Specification and Calculation

Description	Specification
Displacement	942cc
Bore X Stroke	100mm X 120mm
Maximum Torque	400Nm
Maximum Power	90 KW at 2600 RPM
SFC	205 g/KWH
Compression Ratio	17.5:1
EGR System	Cooled

Table 1: Engine Specifications

Calculation for mass flow rate of exhaust and the temperature of the exhaust-

Swept Volume of Engine (Vs):

$$Vs = (\pi/4)*D2*L$$

Volume Swept by piston/min.-

$$Vs= (\pi/4)*(0.1)2*0.12*(1600/2)*4$$

$$Vs = 3.016\ m3/min.$$

Rate of volume flow rate of air into the engine-

$$V = \eta_v*Vs$$

$$V = 0.9*3.016$$

$$V = 2.7143\ m3/min.$$

$$=0.04524\ m3/s$$

Mass flow of air into the engine-

$$m_a = PV/RT$$

$$= 1.2*10^5*0.04524/(287*310)$$

$$m_a = 0.061\ kg/s$$

We use 10-20% of exhaust gases into the engine intake manifold-

$$m_g = m_a + m_f$$

$$m_g = m_a + m_a /20$$

$$m_g= 0.061+(0.061/20)$$

$$m_g = 0.06407\ kg/s$$

Now if 15% exhaust gas taking into the engine-

$$= 0.06407*(15/100)$$

$$= 0.00961\ kg/s$$

Inlet condition- P_1 =1.2 bar T_1=310 K

Taking Isentropic Condition in process 1-2

$$P_1\ (V_1)^{\gamma} = P_2\ (V_2)^{\gamma}$$

$$P_2 = 1.2*(17.5)^{1.4}$$

$$P_2 = 65.983\ bar$$

$$T_2/T_1 = (P_2 /P_1)^{(\gamma-1/\gamma)}$$

$$T_2 = 974.04K$$

$$ER = 7 = r/\rho$$

Cut off Ratio-

$$\rho = 2.5$$

$$\rho_c = T3/T2 = V3 /V2 = 2.5$$

$$T3 = 2435.10\ K$$

$$T4 = T3*(V3/V4)\ (\Upsilon-1)$$

$$T4 = 1118.09\ K\ ,\ P4=4.328\ bar$$

V. Analytical Design Calculations For EGR Cooler

S.No.	Properties	Hot Gas	Coolant (Water)
1	Density(kg/m$^{3)}$	0.257	1000
2	Thermal Conductivity (W/m-K)	0.0732	0.637
3	Viscosity (kg/m-s)	0.45 x 10^{-4}	0.596 x 10^{-3}
4	Prandtl No.($P_{r)}$	0.9651	3.91
5	Specific Heat (KJ/kg-K)	1.323	4.18
6	Mass Flow Rate (kg/s)	0.00961	0.01

7	Inlet Temperature of EGR Cooler(K)	118.09	310

Table 2: Fluid Properties

NTU Method:

Heat capacity of hot gases

$= m_h c_{ph} = 0.01111$ KJ/s-K

Heat capacity of cooling water

$= m_c c_{pc} = 0.0418$ KJ/s-K

Heat capacity ratio

$R = C_{min}/C_{max} = 0.266$

Assuming overall heat transfer coefficient U for gases is 70 W/m^2K

Surface Area of tubes from the design

$A_s = 133513.5\ mm^2$

$= 0.1335135\ m^2$

$NTU = UA/C_{min} = 0.841$

Effectiveness for counter flow EGR cooler

$$\varepsilon = \frac{1 - \exp[-NTU(1-R)]}{1 - R\exp[-NTU(1-R)]}$$

After substituting the values

$\varepsilon = 53.7756$ %

Hot gas exit temperature

$$\varepsilon = \frac{Ch(Thi - Tho)}{Cmin(Thi - Tci)}$$

$T_{ho} = 683.5347$ K

Cold fluid exit temperature

$$\varepsilon = \frac{Cc(Tco - Tci)}{Cmin(Thi - Tci)}$$

$T_{co} = 425.5$K

Kern's Method to Design EGR Cooler

$Q = UAT_{LMTD}$ ……………… (1) $TLMTD = \frac{\theta 1 - \theta 2}{\ln[\frac{\theta 1}{\theta 2}]}$

Where

$\theta_1 = (T_{hi}-T_{co}) = 692.59$ K

And $\theta_2 = (T_{ho}-T_{ci}) = 373.5347$ K

$T_{LMTD} = 516.75$ K

$Q = mc_p(T_{hi}-T_{ho})$

Q = 4.8279 KW

Putting this value in equation (1) to calculate area-

$A = 0.13346879\ m^2$

Since in the design of heat exchanger tube diameter, tube thickness, and tube material are independent variables. Taking dimensions of EGR cooler

Tube material = aluminium (237 W/m-K)

Tube outer diameter = 12mm

Tube thickness = 1mm

VI. Modelling Of The EGR Cooler In PTC Creo

Based on the present EGR system, an EGR cooler model is assembled from totally different components within the modeling setup of CREO Parameter 2.0. The designed EGR cooler could be a counter current, shell and tube device. The views of the first geometry are shown within the modeling section. The modeling options of EGR cooler are as follows:

Sr. No.	Description	Value
1	Shell Inner Diameter	89 mm
2	Shell Outer Diameter	95 mm
3	Shell Thickness	3 mm
4	Tube Inner Diameter	10 mm
5	Tube Outer Diameter	12 mm
6	Tube Thickness	1 mm
7	Tube Length	200 mm
8	Number of Tubes	3

Table 3: Design Features of Existing EGR Cooler

The all part of EGR cooler is assembled which is shown below:

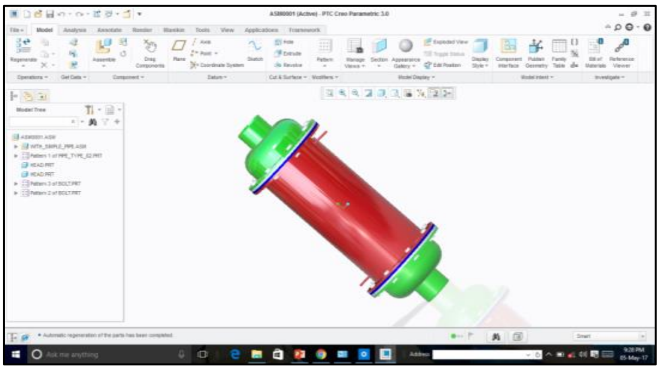

Fig. 1: Assembly of all part of EGR Cooler

The exploded view of assembly is shown below-

The exploded view of assembly with simple tube.

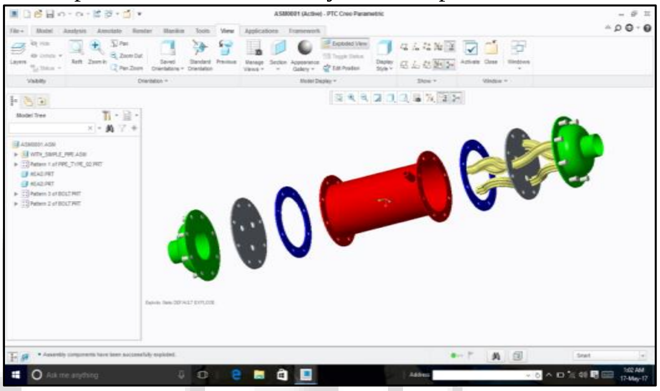

Fig. 2: Exploded view of assembly with simple tube

The exploded view of assembly with square fin tube.

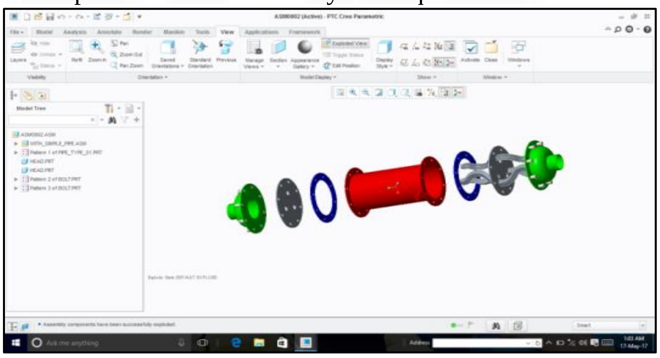

Fig. 3: Exploded view of assembly with square fin tube.

The exploded view of assembly with triangular fin tube.

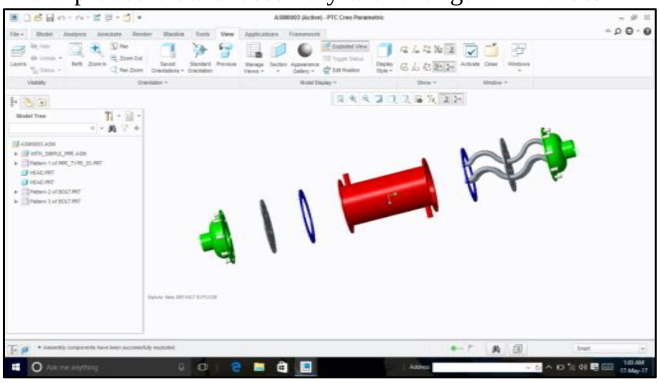

Fig. 4: Exploded view of assembly with triangular fin tube.

VII. THERMAL ANALYSIS OF EGR COOLER AND CFD SIMULATION ON ANSYS FLUENT

Various steps in ANSYS (fluent) as follows:
1) Import Geometry
2) Generation of Mesh
3) Setup of Geometry
4) Solution
5) Results

Case 1: Import Geometry (EGR Cooler with simple tube without fin) and generating mesh.
Cross section of an EGR Cooler with simple tube without fin.

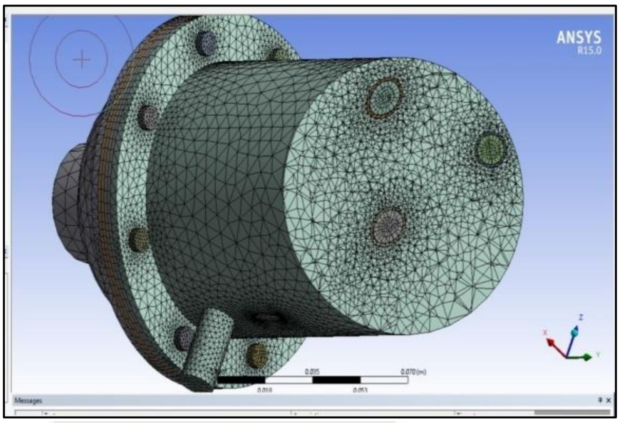

Fig. 5: Transverse cross section of an EGR Cooler with simple tube without fin.

Case 2: Import Geometry (EGR Cooler with Triangular Fin) and generating mesh.

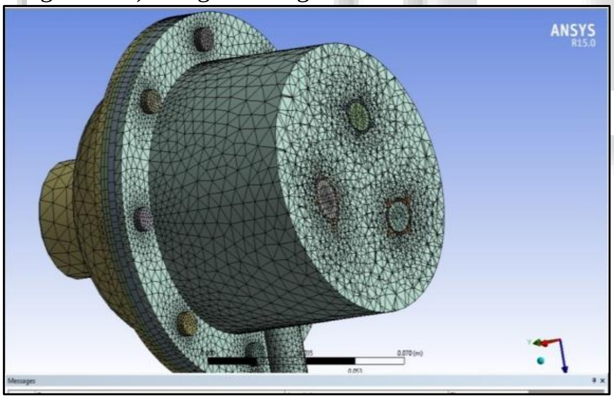

Fig. 6: Transverse cross section of an EGR Cooler with Triangular Fin

Case 3: Import Geometry of EGR Cooler with square fin tube and generating mesh.

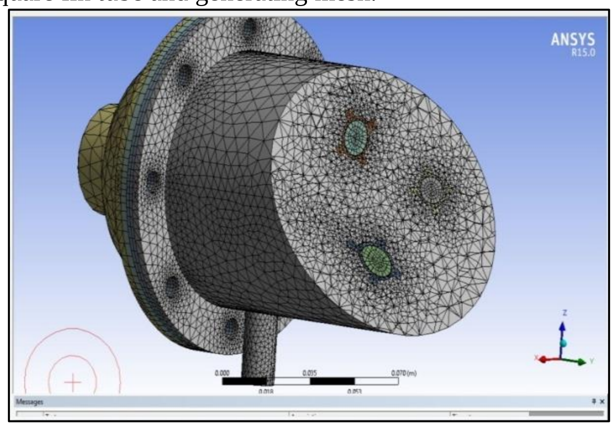

Fig. 7: Transverse cross section of an EGR Cooler with Triangular Fin tube

Above figures are models of various kinds of EGR coolers that are utilized in the analysis. Model- A is a complete assembly of EGR cooler (shell and tube kind of simple-tube). Model-B shows an EGR cooler (3-tubes) with sq. fins. Model- C shows an EGR cooler with triangular fins (3-tubes) these fins are connected on the tube length. Each model are designed within the Creo CAD-software and utilized in the ANASYS for the analysis and to calculate the various kind of parameter for the EGR cooler. Here the most important objective to use ANSYS (fluent) for simulation is to calculate the Effectiveness of various models-A, B, and C. ANSYS can offer us temperature profile of the various models in keeping with the boundary conditions applied by us. From the temperature profile of the model we are able to simply calculate the effectiveness of that EGR cooler and compare all the models as per their effectiveness.

VIII. THERMAL ANALYSIS

In the setup method, double click on setup then setup window is opened. Then we click on 'models' set the Energy equation 'on', and then choose k-ε turbulent from 'viscous' tab. Now choose 'materials', by 'create/edit' button, Select materials from the 'fluent material library' and it will be altered and implemented to the 'solver'. Add 'water' and 'hot-gas' with the subsequent properties from Table-3.1. Now we choose the 'Cell Zone Condition', here the state of material type will be assigned to choose elements of the assembly. Problem solver can treat these elements by their material state. Now click on 'Boundary conditions', here all the boundary conditions of various 'Named Selection' will be assigned. Now the 'Solution Methods' to its defaults values, proceed to 'Solution Initialization', so press 'Initialize' button then 'Run Calculation'. Set range of iterations to converged solution and this calculation are performed until the desired number of iterations. Convergence within the resolution is obtained before nth iteration; once resolution is completed we will read and plot results.

The temperature contour of the models shows the variation of temperature on the tube red color shows the intake temperature of exhaust gases as gases move forward heat is extracted by the coolant water and temperature of gases reduced and also the temperature of the fluid are raised as it takes heat from exhaust gases. Green color shows the outlet temperature of exhaust gases. Blue color shows the temperature of coolant.

As we aren't ready to differentiate the change in temperature of coolant within the temperature contour as changes in temperature happens only in blue zone of temperature contour. And therefore the magnitude of temperature at any point is measure by matching the color at that time to the color or scale. Temperature contours for various Models as follows:

Thermal Analysis of Simple Tube:

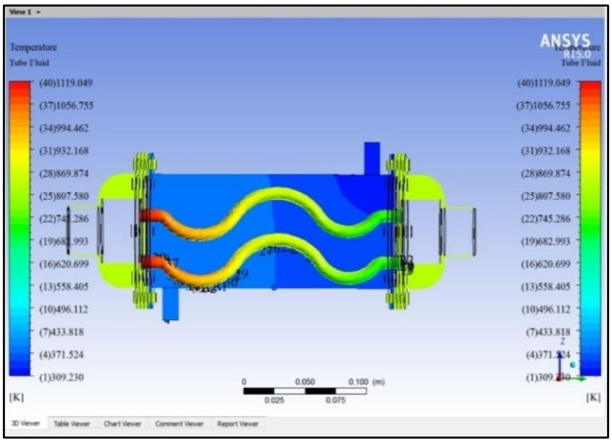

Fig. 8: Thermal analysis of EGR Cooler with simple tube without fin.

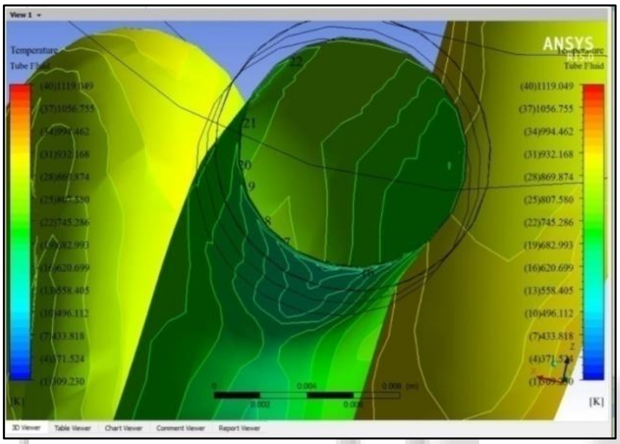

Fig. 9: Effect of Temperature on hot gas with simple tube without fin

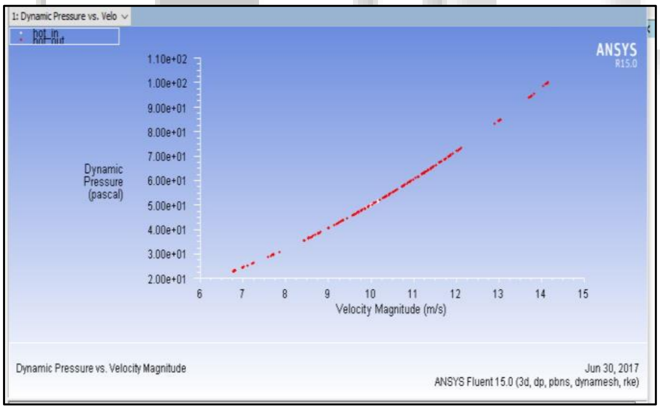

Fig. 10: Dynamic pressure vs. velocity magnitude

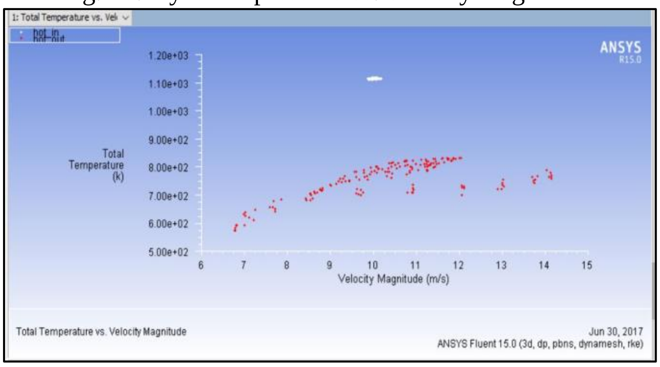

Fig. 11: Total temperature vs. velocity magnitude

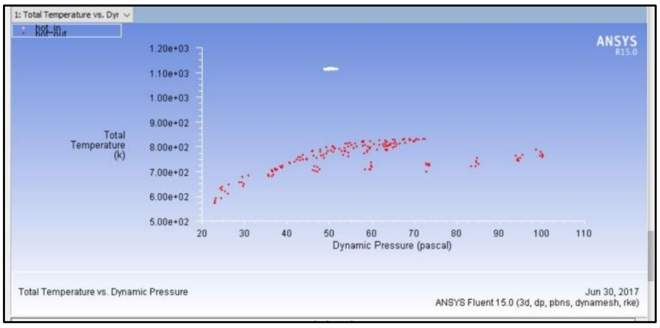

Fig. 12: Total temperatures vs. Dynamic Pressure

No. of tube	Types of Tube	Inlet Hot gas temp. (K)	Outlet Hot Gas temp. (K)	Inlet cold Fluid temp. (K)	Outlet cold Fluid temp. (K)	Effectiveness (%)
3	Simple	1118	683	310	352	53.84

Table 4: Output Result For Simple Tube

$$\varepsilon = \frac{Ch(Thi - Tho)}{Cmin(Thi - Tci)}$$

$$\varepsilon = 53.84\ \%$$

Thermal analysis of Triangular fin Tube:

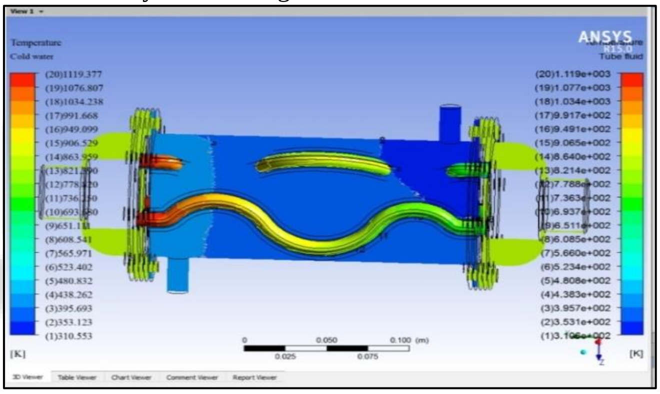

Fig. 13: Thermal analysis of EGR Cooler with triangular fin tube

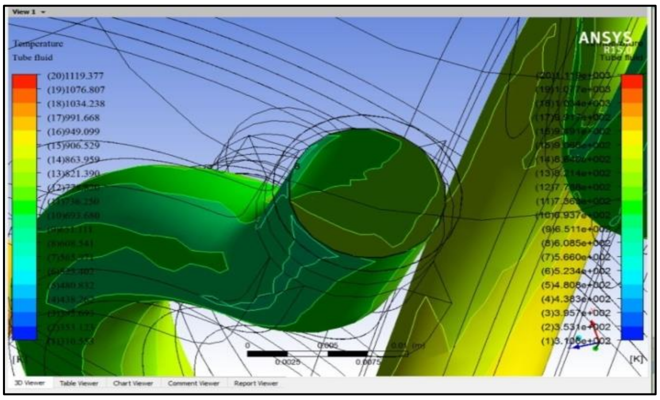

Fig. 14: Effect of Temperature on hot gas with triangular fin tube.

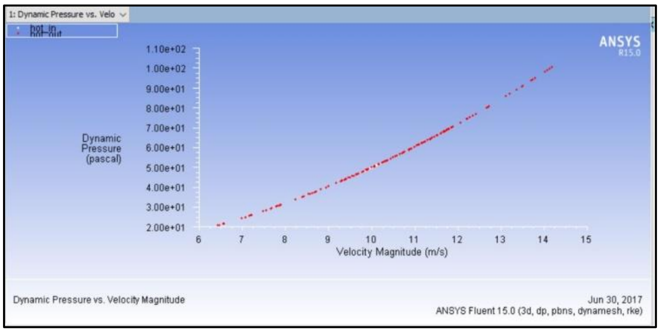

Fig. 15: Dynamic Pressure vs. Velocity Magnitude

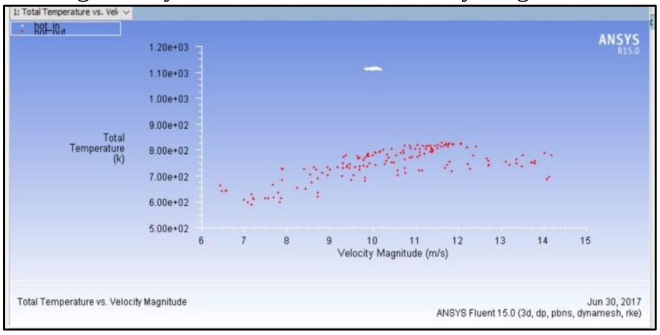

Fig. 16: Total temperature vs. velocity magnitude

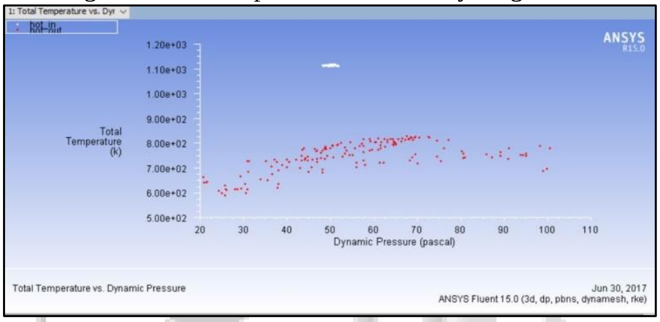

Fig. 17: Total Temperature vs. Dynamic Pressure

$$\varepsilon = \frac{Ch(Thi - Tho)}{Cmin(Thi - Tci)}$$

$$\varepsilon = 63.123\ \%$$

No. of tubes	Types of Tube	Inlet Hot gas temp(K)	Outlet Hot Gas temp. (K)	Inlet cold Fluid temp.(K)	Outlet cold Fluid temp.(K)	Effectiveness (%)
3	Triangular Fin	1118	608	310	395	63.123

Table 5: Output Result for Triangular Fin Tube

Thermal analysis of Square fin Tube:

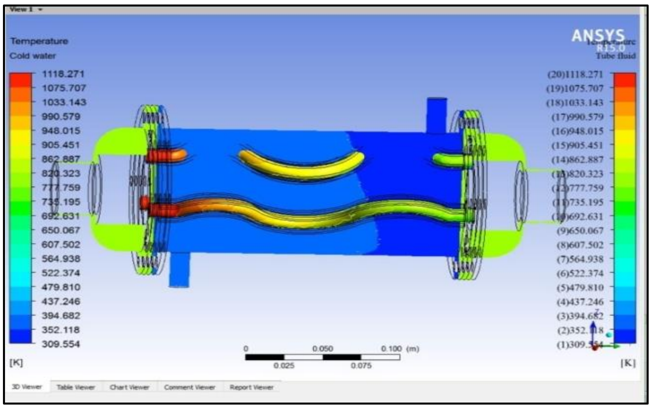

Fig. 18: Thermal analysis of hot gas with square fin tube

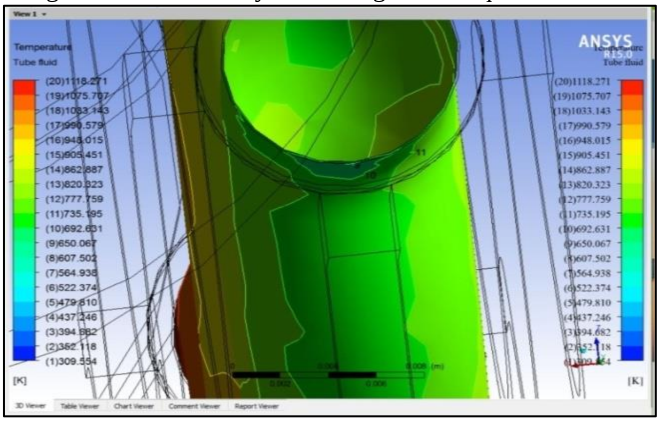

Fig. 19: Effect of Temperature on hot gas with square fin tube.

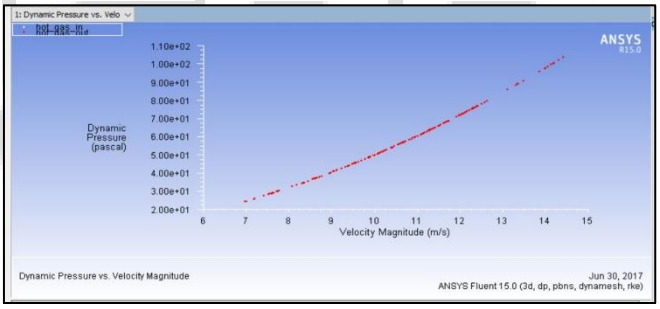

Fig. 20: Dynamic Pressure vs. Velocity Magnitude

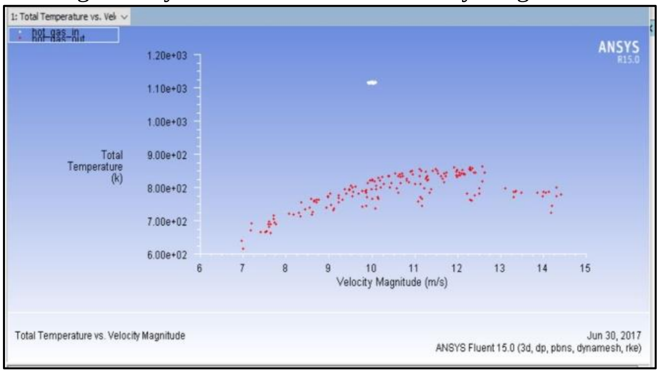

Fig. 21: Total Temperature vs. Velocity Magnitude

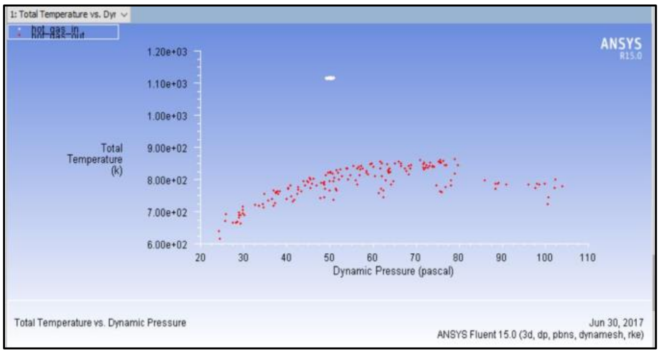

Fig. 22: Total Temperature vs. Dynamic Pressure

$$\varepsilon = \frac{Ch(Thi - Tho)}{Cmin(Thi - Tci)}$$

$$\varepsilon = 61.64\%$$

No. of tube	Types of Tube	Inlet hot temp.(k)	Outlet hot temp. (K)	Inlet cold temp (K).	Outlet cold temp. (K)	Effectiveness (%)
3	Square	1118	620	310	371	61.64

Table 6: Output Result for Square Fin Tube

S No.	Types of Tube	Inlet hot temp.(K)	Outlet hot temp. (K)	Inlet cold temp. (K)	Outlet cold temp. (K)	Effectiveness (%)
1	Simple	1118	650	310	352	53.84
2	Triangular Fin	1118	608	310	395	63.123
3	Square Fin	1118	620	310	371	61.64

Table 7: Result Comparison of All Tubes

IX. Comparison Charts

A. Comparison chart of temperature

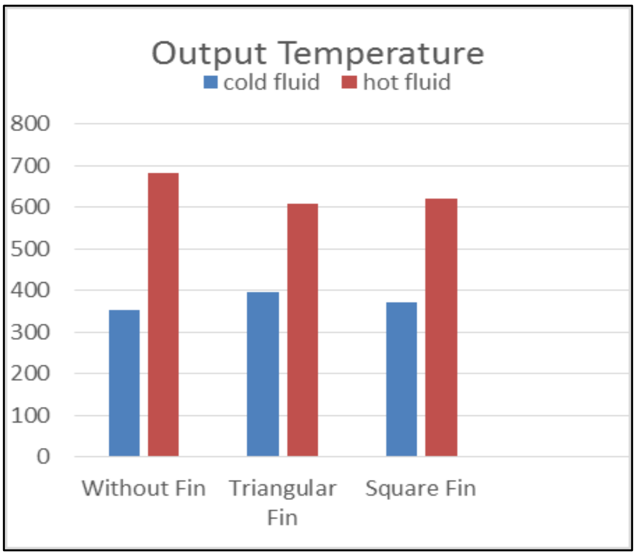

Fig. 23: Comparison chart

B. Comparison chart of effectiveness

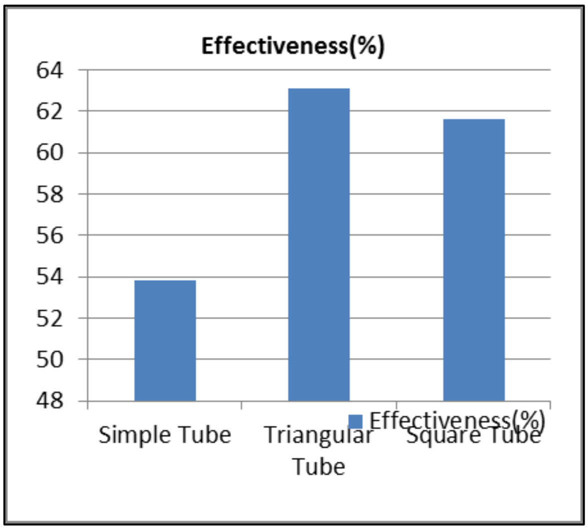

Fig. 24: Comparison chart of effectiveness

C. Flame Temperature Correlation

Several investigators have used the characteristics of straightforward diffusion flames to model diesel combustion and Nox production in internal-combustion engine. Sawyer et al. argued that Nox emissions from diesel engines ought to correlate with the adiabatic flame temperature similar to in turbine and different steady-flow combustors. Since most of the diesel burns within the scattered burning section and Nox forms primarily within the burned – gas region, we are able to resume that almost the entire diesel burns within the diffusion section. Hence, the adiabatic stoichiometric Flame Temperature calculated at begin of combustion ought to correlate well with Nox emissions. This Nox created will be represented by an equation of the form-

$$EI_{NOX} = C_{mix}\, e^{(-38700/T_f)}$$

Where-

C_{mix} = mixing factor dependent on speed and load but not on intake composition.

EI_{NOX} = Emission Index. NO_X in grams/kg of fuel

T_f = Calculated adiabatic- stoichiometric flame temperature at start of combustion.

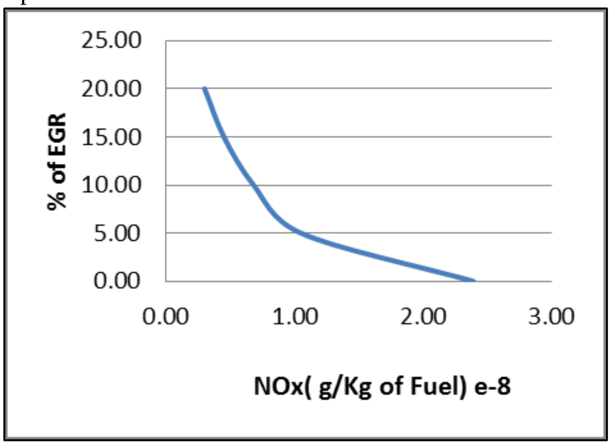

Fig. 25: % of EGR vs. NOx

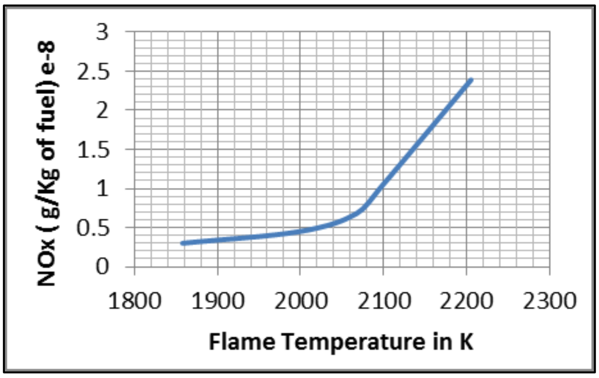

Fig. 26: NOx vs. Flame Temperature

It is seen from the graph and table, as we increase the EGR rate the quantity of Nox is decrease in proportional of share of EGR. As Nox is directly depends on the flame temperature, as flame temperature decrease Nox too decrease. So, we get 87 of Nox reduction once 200th of EGR is implied.

X. Conclusion

On the analysis of CFD Simulation we discover that the effectiveness of EGR cooler with triangular fin is beyond the other model thus for higher result and reducing Nox share we like the EGR cooler with triangular fin.

The variation of temperatures with speed and dynamic pressure at various completely different} points and therefore the variation of dynamic pressure with speed at different points are shown in graphs for straightforward tube, triangular fin tube and sq. fin tube.

The conventional methodology used for testing and performance for a heat exchanger (EGR cooler) is extremely overpriced and consumes much time. However the technique presently offered i.e. CFD analysis technique is fast and correct as compared to the traditional methodology. So CFD is extremely necessary tool for modeling and development of shell & tube kind of EGR cooler as this reduces the time and value in developing the model of planned style and testing. it's clear from the results that in Model-1, once tubes are replaced by sq. finned type of tube, its effectiveness is magnified by 7.8 % and, once further it's replaced by triangular finned tube its effectiveness is magnified by 9.283 which is similar as compared to Model-1. Thus Model-3 is most effective as compared to others and it's additionally cut back the share of Nox than the different models so we will like this to be used. It's additionally magnified the effectiveness by increasing the no. of tubes.

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