Design, Modeling and CFD Analysis of EGR Cooler for Future Emission Norms of Diesel Engine

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Abstract – Diesel engines are important power train solution for heavy duty vehicles. As the Bharat Stage emission norms are become stringent because of health and environmental issue hence it is essential to reduce pollutant emission. Exhaust gas recirculation(EGR) is one of the best method to reduce NOx emission. To use EGR concept effectively it is necessary to develop an effective EGR cooler with high rate of heat duty and compact in nature. Hence in this study theoretical analysis and CFD simulation of EGR cooler is carried out for improved emission and high heat recovery from engine exhaust. Experiments are carried out on CRDI engine with three types of EGR cooler and results are compared with development model. It was observed that there is good agreement between experimental results and prediction from the development model.

Keywords: *EGR cooler , CFD, Exhaust gas, Emission,*

Nomenclature
Nu- Nusselt number
Re- Reynold number
Pr- Prandtl number
ΔTm- Logarithmic temperature difference (°C)
A-Overall heat transfer area (m^{2})
Uo – Overall heat transfer coefficient ($W/m^{2\circ}C$)
Nt- Number of tubes
ΔP- Pressure drop (mbar)
do- Outside diameter of tube (m)
di- Inside diameter of tube (m)
ho – Shell side heat transfer coefficient
hi – Tube side heat transfer coefficient
Ds –Diameter of shell (m)
De- Equivalent diameter of shell (m)
Gs- Grashoff number
$\dot{m}_a$- mass flow rate of air (kg/s)
$\dot{m}_g$ – mass flow rate of exhaust gas(kg/s)
Cp_a- specific heat of air
Cp_g – specific heat of exhaust gas

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I. INTRODUCTION

As response of regulation induced around the world to limit the pollutant emissions associated with diesel engine, researchers and manufactures are focusing their effects on developing new technologies to fulfill restrictive limitations.

There are different types of methods are present to reduce the NOx emissions such as diesel oxidation catalyst , diesel particulate filter , selective catalytic reduction . But this method is not enough to reduce emission hence EGR method is effective method to reduce emissions and achieve BS-6 norms.

EGR is technique that can reduce NOx emissions in CI engine where fraction of exhaust gas are required through control valve from exhaust to the engine intake system [6]. NOx consist of NO and NO2 ; retarded injection is effective method to reduce NOx but this method causes increased fuel consumption, reduced power, increased HC emissions and smoke .mixing of exhaust gas with intake air increases specific heat of intake and reduce combustion temperature. Combination of lower oxygen quantity in intake air and reduce flame temperature reduces NOx formation. A portion of the exhaust gases is recirculated into the combustion chambers. This can be achieved either internally with the proper valve timing externally with some kind of piping.

The exhaust gas acts as an inert gas in the combustion chamber, it does not participate in the combustion reaction. Another effect is the change in heat capacity. Exhaust gas has a higher specific heat capacity than air, due to the CO2-molecule's higher degree of freedom. So for the same amount of combustion energy a gas mass containing EGR will get a lower temperature than pure air. The lower combustion temperature directly reduces the NOX formation, as the NOX formation rate is highly temperature dependent [8]. There are different type of EGR system such as hot ,cold EGR and low pressure ,high pressure EGR system is present.

Exhaust gas reduces NOx emission by 60 % when the EGR rate is maintained between 10 % to 50% [15]. Hybrid EGR is effective method to reduce NOx emissions. As the EGR rate increases soot emission also increases [17]. Long route system present attractive features in terms of lower back pressure, high achievable EGR rate and mass flow, higher efficiency of the compressor and turbine operating points and great margin from surge line [10]. The combined effect of cooled EGR and high compression ratio improves brake thermal efficiency of engine [8]. Higher EGR rate increases NOx emission hence 15% to 30 % EGR rate is optimum for maintaining lower NOx emission Due to EGR. NOx and CO emission reduces but HC emission remains same [16]. The application of EGR also adversely affects the lubricating oil quantity and engine durability. Thermal efficiency of Engine increases at lower load and remain unaffected at higher load. Volumetric efficiency decreases due to effect of EGR.

Long circuit EGR is more effective than short circuit EGR. Using spiral tubes will be very effective in scope of equalizing fluid speed in shell ,local boiling and thermal stress obstruction and intensifying perpetuity of cooler. Spiral tube usage promotes growth of heat transfer efficiency in tube side and reduction of cooler size and weight. However it will induce pressure drop increment in tube side. Pitch size reduction and spiral depth increment are effective factors at heat transfer and pressure drop growth [12]. shell and tube heat exchanger tube side heat transfer performance must be significantly high while the shell side resistance must be significantly low. Material used for making EGR cooler is stainless steel. It is found that tube side pressure of the corrugated pipe configuration is remarkably higher than that of the smooth pipe configuration . It is showed that tube side temperature of the corrugated pipe configuration decreases more quickly than corrugated side pressure drop [13]. Helical baffle enhances heat transfer in shell and tube heat exchanger significantly. Sealers is used to improve efficiency of EGR cooler. For all solid walls ,no slip and no penetration boundary conditions are were considered. The heat transfer efficiency of the s-spiral EGR cooler is 0.17 higher than that of F- smooth EGR cooler under identical tube side Reynold number. The result show that the geometric structure of semi spiral cooling system is better than full smooth cooling system. Heat transfer efficiency of F-spiral EGR cooler is more than S-spiral EGR cooler but considering pressure drop S- spiral tube EGR cooler is suggested [6].

Higher capacity engine used in most of the commercial vehicle. Hence 3250 CC engine is selected for finding out effect of EGR cooler on pollutant emissions Hence In this paper theoretical model of EGR cooler is developed for 3250 CRDI engine and its is compared with other EGR coolers.

II. MATERIALS AND METHODS

In experimental setup low pressure EGR system is used for finding out the optimum performance of EGR cooler.

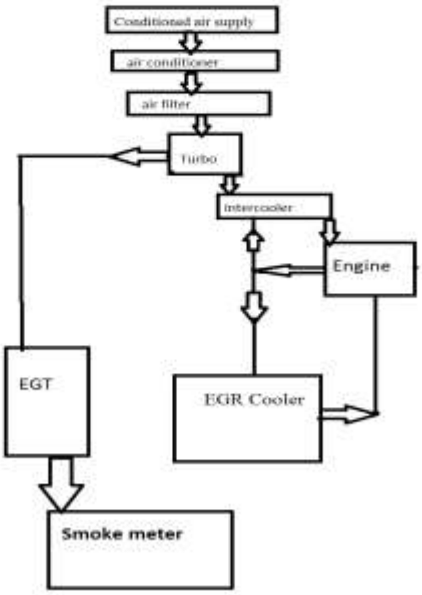

Figure 1: Experimental Setup

Table 1: Equipments used in Experimental Setup

Equipment	Specification and use
Five cylinder CRDI diesel engine	Oil cooled, 85 KW @2800 rpm
Thermocouple	RTD , thermocouples
Pressure measuring device	Sensor
Intercooler circuit	Heat exchanger
Transient Dyno	For running the engine. (Make : AVL)
Gas analyzer	For measuring NOx, CO, HC emission.(Make : Horiba)
Fuel flow meter	Weight balanced flow meter
Coolant conditioning system	For maintaining coolant flow constant
Opacimeter	For checking opacity .(Make : Horiba)
Smoke meter	For smoke measurement .(Make : Horiba)
Air conditioning system	For inlet air conditioner (Make : AVL)

For experiments, five cylinder CRDI engine is coupled with transient dyno. RPM of the engine is varied by varying load on transient dyno. Temperature and pressure of exhaust gas and other engine fluid is measured by sensors. Exhaust gas analyzer is used for measuring pollutant emissions.

WHSC cycle is used for finding out feasibility of EGR cooler on engine .Inlet temperature of exhaust gas is 450° - 500 °C and coolant is 68°C. Flow rate of Exhaust gas and coolant is 125 kg/hr and 20 lpm respectively.

Engine specification is shown in Table 2 as follows:

Table 2: Engine Specification

Parameters	Description
Type	Inline Five cylinder, 4 stroke ,CRDI engine
Power	90 KW @2950 rpm
Peak torque	320 Nm@ 1400-2400 rpm
Bore X Stroke	90.5X 90.9
Compression ratio	16.5:1

Mathematical formulation

Design of heat exchanger is done by LMTD method and tubular exchangers manufacturers association standard. Also permissible amount of pressure drop is measured by related equation.

In the LMTD method heat transfer is calculated by following method

$$A = \frac{Q}{Uo * \Delta Tm}$$

Logarithmic temperature difference can be calculated as :
ΔT2=Th1-Tc2

ΔT2=Th2-Tc1

$$\Delta Tm = \frac{\Delta T1 - \Delta T2}{\ln\left(\frac{\Delta T1}{\Delta T2}\right)}$$

Overall heat transfer coefficient can be calculated as:

$$Uo = \frac{1}{\frac{d0}{di} * hi + do * \frac{\ln\left(\frac{do}{di}\right)}{2K} + \frac{1}{ho}}$$

Bell Delware method is used to calculate heat transfer coefficient.

Shell side heat transfer coefficient can be calculated as:

ho = ji* Cp* (ms/As) *(K/Cp*µs)^(2/3) * (µ/µs*w)^0.14

Tube side heat transfer coefficient can be calculated as:

$$Nu = \frac{\left(\frac{f}{2}\right) * Re * Pr}{1.07 + 12.7\left(\frac{f}{2}\right)^{\frac{1}{2}} * \left(\left(Pr^{0.5}\right) - 1\right)}$$

Pressure drop at tube side:

$$\Delta P = \frac{f * Gs^2 * (Nb + 1) * Ds}{2 * \rho * De * \emptyset s}$$

Pressure drop at shell side:

$$\Delta P = 4 * f * \left(L * \frac{Np}{dt}\right) * \left(\frac{Gt^2}{2\rho}\right)$$

In below table EGR cooler 4 is theoretical model . Parameters of the EGR cooler model is find by above equations.

Table 3: Parameters of EGR Coolers

Parameters	**EGR cooler 1**	**EGR cooler 2**	**EGR cooler 3**	**EGR cooler 4**
No of tubes	-	28	-	25
No of baffles	-	3	-	4
Tube length	190	180	260	220 mm
Total length	220	230	300	296 mm
Inlet coolant side diameter	14	19.5	21	18 mm
Outlet coolant side diameter	14	19.5	16	16 mm
Inlet exhaust gas side diameter / CS area	48*65	30	119* 86	40 mm
Outlet exhaust gas side diameter	48 *65	30	119 *86	40 mm
Material	Stainless steel	Stainless steel	Stainless steel	Stainless steel

CFD model

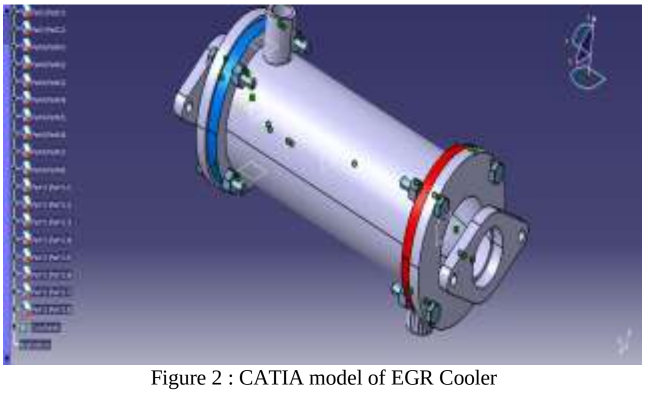

Figure 2 : CATIA model of EGR Cooler

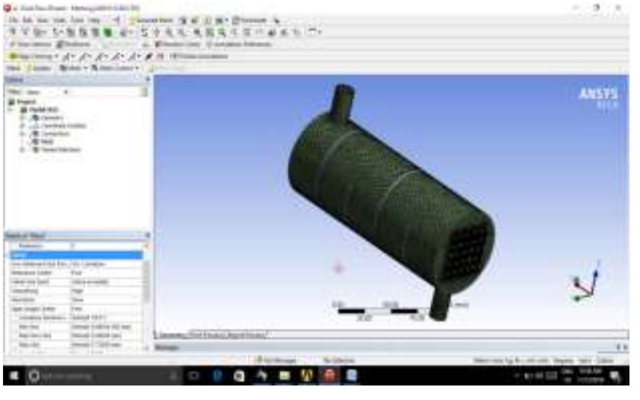

Figure 3: Meshing of EGR cooler in ANSYS Fluent

Table 4: Meshing Condition

Parameters	Dimension
Relevance center	Fine
Initial size seed	Active assembly
Smoothing	High
Transition	Slow
Method	Triangular Mesh
Number of elements	1660211
Number of nodes	2684300

Fluent 14.0 is use to simulate the setup to find the pressure and temperature distribution .. Pressure based solver is selected. Steady condition is applied. In models ' Energy model' is activated to support temperature calculations. Material properties like density or kinematic viscosity is set depending on temperature value from air properties. Standard k-ε model is used. Air is used as exhaust gas. Exhaust gas properties are applied to air. Stainless steel SS30L properties are applied to steel. steel is used for wall of shell and pipe. For Baffle and sealers steel is used. In Shell inlet Ethylene glycol is flowing and in pipe inlet air is flowing.

Fluent 14.0 is use to simulate solution control. Pressure velocity coupling simple scheme is used. Gradient used is least square based. Momentum and turbulence Kinetic energy is set. second order upwind and turbulence dissipation rate is first order upwind. Hybrid initialization method is used.

III. RESULTS AND DISCUSSION

In present work, the main aim is to simulate the flow that exist in EGR cooler and thereby study the performance of EGR cooler on the basis of temperature drop, pressure drop and velocity flow of exhaust gas and coolant.

1.Temperature disitibution

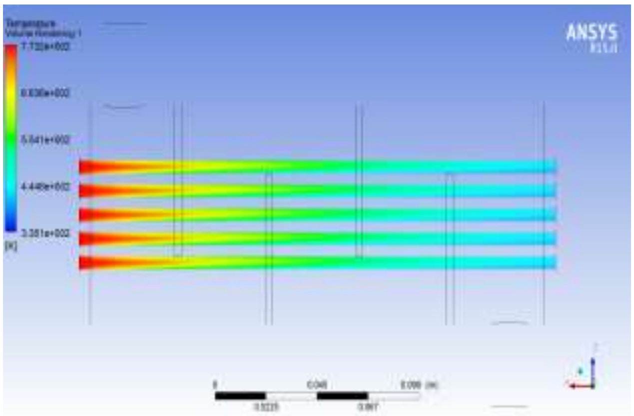

Figure 4: CFD Temperature result

Table 5 : CFD Temperature Result

EGR cooler sections	Resultant Temperature(°C)
Exhaust gas inlet	500
Exhaust gas outlet	165
Coolant inlet	68
Coolant outlet	70

Temperature variation is shown in above figures. These are two main zones . One is shell and other is fluid domain zone. Red color shows the higher temperature and as the exhaust gas passes through tube color variation take place. Blue color shows lower temperature.

3. Pressure distribution

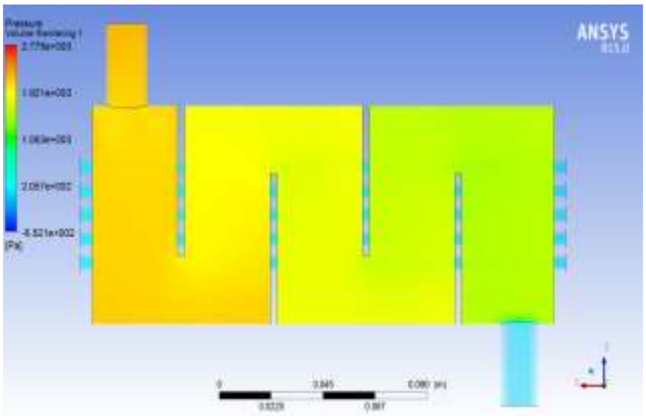

Figure 5: CFD Pressure result

Pressure simulation is shown above figures. Pressure simulation is one of the important aspect in the designing of heat exchanger. Because from this study we can make the conclusion about the safety of the design of our heat exchanger. On tube side there is light blue color can see. Variation in tube side is less . On shell side there is large amount of pressure drop . at inlet there is yellowish color and outlet there is bluish color can be seen.

Table 6: CFD Pressure Result

EGR cooler sections	Resultant Pressure(pascal)
Exhaust gas inlet	1600
Exhaust gas outlet	1152
Coolant inlet	2191
Coolant outlet	1952

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2. Velocity distribution

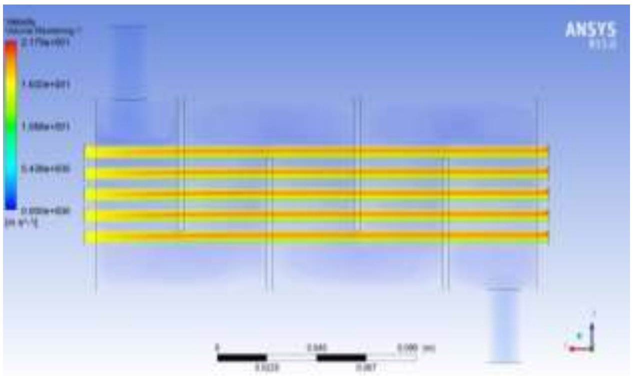

Figure 6: CFD Velocity Result

At outlet result velocity at exhaust gas outlet is 12.12 m/s. At outlet of coolant tubes resultant velocity is 1.031 m/s. Velocity streamline shows flow of coolant in shell.

Table 7: CFD Velocity Result

EGR cooler section	Resultant velocity
Exhaust gas inlet	15.87
Exhaust gas outlet	12.12
Coolant inlet	1.311
Coolant outlet	1.013

Comparative Study of Theoretical Model with other EGR Coolers.

For validating CFD model ; CFD model result is compared with EGR cooler testing data.

1. Temperature of exhaust gas at inlet of EGR cooler

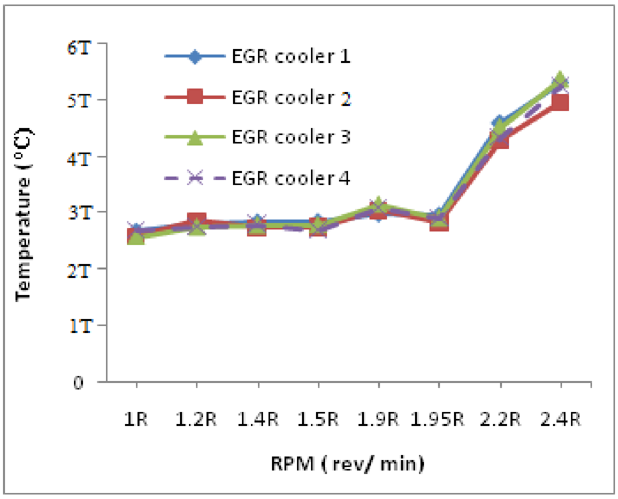

Figure 7: Temperature of Exhaust Gas at Inlet of EGR Cooler at Different Engine RPM

Temperature of exhaust gas at inlet of EGR cooler is almost same due to position of EGR cooler on Engine. There is increase in exhaust gas temperature as the RPM increases.

2. Temperature of exhaust gas at outlet of EGR cooler

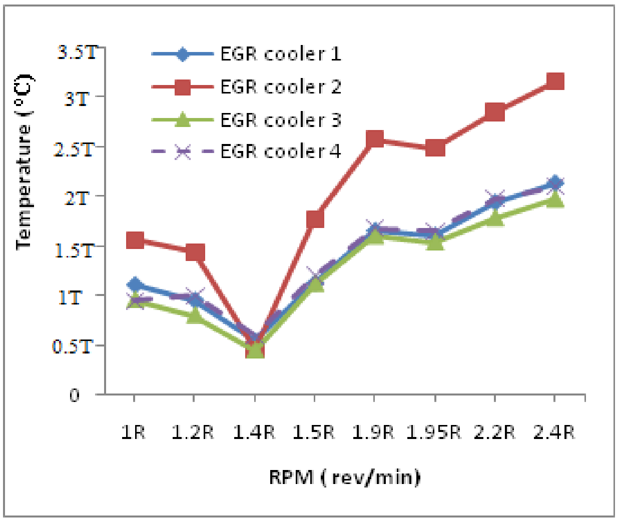

Figure 8: Temperature of Exhaust Gas at outlet of EGR Cooler at Different Engine RPM

For EGR cooler 2 temperature of exhaust gas at outlet is more as compared to other EGR coolers. EGR cooler 2 and theoretical model has almost same temperature .

3. Temperature drop

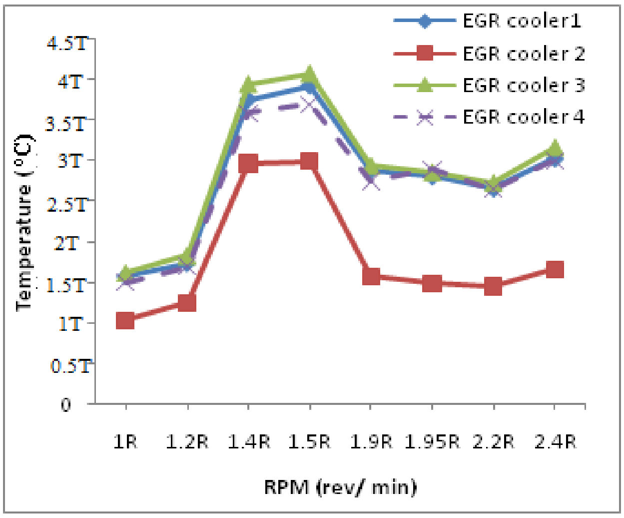

Figure 9: Temperature Drop across EGR cooler at Different Engine RPM

Temperature drop is the temperature difference between inlet exhaust gas temperature and outlet exhaust gas temperature. EGR cooler 4 is the EGR cooler is designed by above theoretical calculation and validated by CFD result. Temperature drop around 300°C to 400° C. As the engine rpm increase above 1400 temperature drop goes on increasing.

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4. Pressure drop

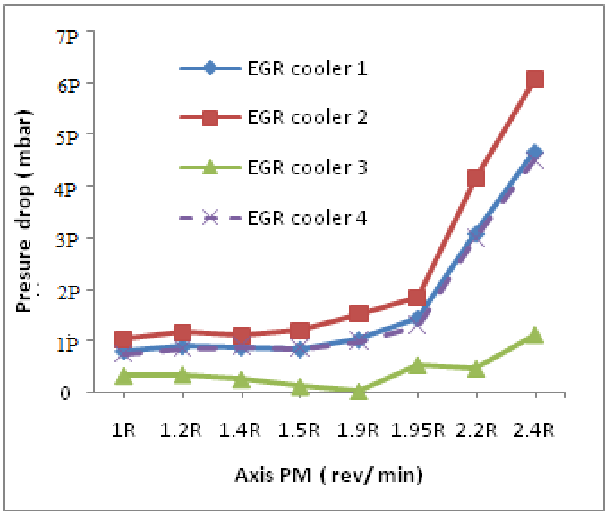

Figure 10: Pressure Drop at Different Engine RPM

Pressure drop is the pressure difference between inlet exhaust gas pressure and outlet exhaust gas pressure. EGR cooler 4 is the EGR cooler is designed by above theoretical calculation and validated by CFD result. Pressure drop is obtained between 200 mbar to 600 mbar. As the engine rpm goes on increasing pressure drop also goes on increasing.

5. CO Emission

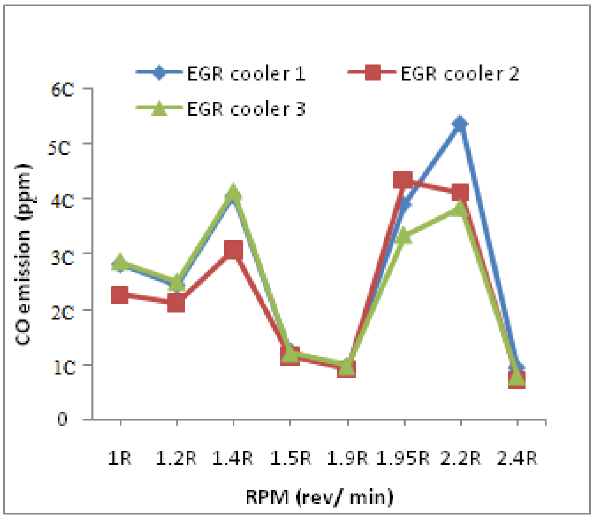

Figure 11: CO Emission at Different Engine RPM

CO emission is minimum for EGR cooler 2 at initial rpm and similar for other EGR cooler. There is Sudden rise in CO emission at higher RPM.

5. HC Emission

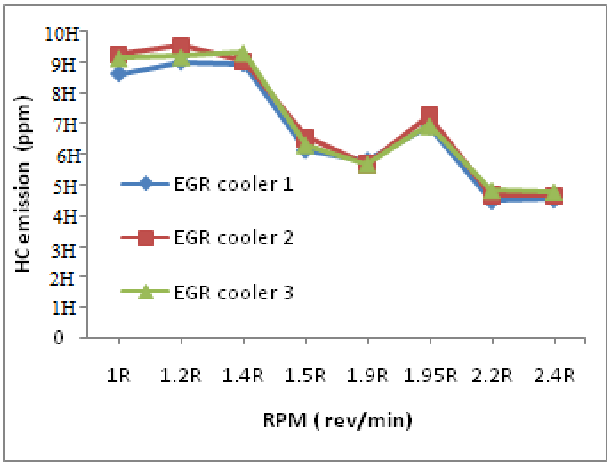

Figure 12: HC Emission at Different Engine RPM

HC emission is measured in ppm. HC emission is same for all EGR cooler. As the RPM increases HC emission decreases.

6 .NOx Emission

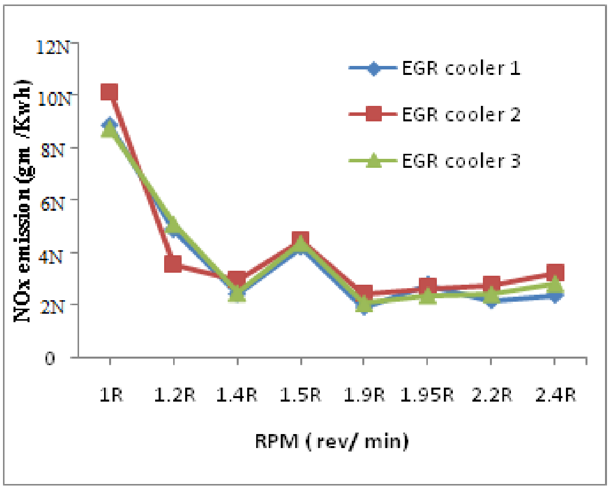

Figure 13: NOX Emission at different Engine RPM

Appropriate amount of EGR can reduce NOx emission significantly. EGR rate should be maintained between 20 % to 30 % . At initial rpm NOx emission is maximum and as the rpm increases NOx emission decreases. For EGR cooler1 NOx emission is around 2.8 gm/Kwh. It is minimum between all EGR cooler.

IV. CONCLUSION

In the present study, theoretical model is developed and predictions from the developed model are compared with experimental results obtained from CRDI engine using optimized EGR cooler. The result indicates that

- As the engine speed increases there is increase in temperature of exhaust gas and pressure drop across EGR cooler.
- It has been also observed that as engine speed increases there is increase in CO,HC emission.
- It has also observed by comparison of result that at higher speed there is decrease in NOx emission even though higher exhaust gas temperature.

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