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Modeling and CFD Simulation of EGR Cooler for CRDI Diesel Engine and Comparison of Various Inlet Manifold

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Abstract: ***Traditionally EGR cooler comes with single inlet for coolant. The CFD analysis is performed on EGR cooler of CRDI engine using different inlet configurations which is two, three and five. Thermal characteristics along with pressure and turbulence is studied which highly affects the heat transfer rate and effectiveness of cooler. The CFD analysis is performed using CFD code ANSYS CFX 14.0. Standard k-epsilon turbulence model.***

Keywords: EGR Cooler, NOx, CFD

1. Introduction

In the nineties, antipollution policies have taken effect in the European commission (directive 91/542/CEE) regarding nitrogen oxides emissions (NOx) in diesel engines. These policies have been accomplished through the development and large utilization of exhaust gases recirculation (EGR) technology to restrict these emissions. The introduction of a fraction of the combustion products through the inlet decreases the oxygen concentration of the admitted mixture slowing down the subsequent process, which drives to lower temperatures during the thermodynamic cycle. Consequently, the EGR system decreases NOx formation through the combustion process with little diminution of the diesel engine performances1,2.

The emission legislation in Europe has brought a reduction in the emission rate from year 2000 to till date. The stringent rules made the compulsory required reduction of HC, NOx and particles to almost half of the Euro 2000 values for diesel passenger cars.

The stringent conditions on emission in latest Euro norms lead to the introduction of a cooler in the EGR system that decreases the gases temperature previously to their recirculation. By means of the diminution of the inlet temperature, EGR-cooler strengthens the effect of NOx emissions reduction caused by recirculation, being also remarkable the diminution of soot emissions. A multi-tube EGR cooler was developed to have high heat exchanger efficiency with high reliability for heavy-duty diesel engine application.

2. Literature Review

Simon Reifarthit [1] It gives an overview of the field of EGR and diesel combustion and presenting the methods used in this work. This work provides a simulative comparison of different EGR systems, such as long-route EGR, short-route EGR, hybrid EGR, a system with a reed valve and a system with an EGR pump. Both the SteadyState performance and transient performance are compared.

Jaffar Hussain et al [2] studied the effect of EGR on performance and emissions in three cylinders, air cooled and constant speed direct injection diesel engine, which is usually used in agricultural farm machinery. Such engines are normally not operated with EGR. The experiments were performed to experimentally evaluate the performance and emissions for different EGR rates of the engine.

B. JothiThirumal et al [3] conducted experiment on the effect of exhaust gas recirculation on the exhaust gas temperature. The experimental set up for proposed experiments was developed on two-cylinder direct injection air cooled compression ignition engine experiment was conducted for observing the effect of
different quantities of EGR on exhaust gas temperature.

Deepak Agarwal et al [4] conducted a test on a single cylinder DI diesel engine and calculated the performance and emission characteristics with rice bran methyl ester (RBME) and its blends as fuel with EGR system. They optimized and reported that 20% biodiesel blends with 15% EGR produce less NOx, CO and HC emissions and also enhanced thermal efficiency and reduced BSFC.

B. Deet al [5] In this paper an experimental study is carried out on an I.C. engine laboratory single cylinder, four-stroke VCR, direct injection diesel engine to analyze the performance and emission characteristics of pure diesel, Jatropha oil and Jatropha oil-diesel blended fuels with different blended rates. The measurements are recorded for the compression ratio of 16, 17 and 18 varying the load from idle to rated load of 3.7 kW. Comparative results are given at constant engine speed, variable compression ratio and various engine loads for pure diesel, Jatropha oil and Jatropha oil-diesel blended fuels revealing the effect of diesel, Jatropha oil and Jatropha- diesel blended fuels combustion on engine performance and exhaust emissions.

Zhang et al. [6] investigated the effect of diesel soot deposition on the performance of a small 6-tube shell and tube heat exchanger by operating the engine at medium load which produced an exhaust gas temperature of around 250 °C. They found that fouling increased the thermal resistance and pressure drop by 150% during 12 hours of exposure. The rate of increase of the thermal resistance decreased over this period and approached an asymptotic value.

3. Proposed Work

The overall objective of this research is to improve effectiveness of EGR by varying shell design using techniques of Computational Fluid Dynamics to achieve better heat transfer rate and effectiveness. The software used for analysis is ANSYS CFX and CAD modeling is done using Creo 2.0. The base design for analysis is taken of CRDI engine. The inlet configuration used for present research is two, three and five. Contour plots of pressure, temperature and velocity are plotted to analyze thermal behavior.

4. Methodology

The research analysis is performed using Computational Fluid Dynamics technique where CAD modeled is developed and imported in ANSYS CFX solver where suitable boundary conditions is applied and solved. The analysis involves three stages, first is pre-processing, solution and post processing stages. A pre-processor is used to define the geometry for the computational domain of interest and generate the mesh of control volumes (for calculations). Generally, the finer the mesh in the areas of large changes the more accurate the solution. Fineness of the grid also determines the computer hardware and calculation time needed. The solver makes the calculations using a numerical solution technique, which can use finite difference, finite element, or spectral methods. Most CFD codes use finite volumes, which is a special finite difference method. First the fluid flow equations are integrated over the control volumes (resulting in the exact conservation of relevant properties for each finite volume), then these integral equations are discretized (producing algebraic equations through converting of the integral fluid flow equations), and finally an iterative method is used to solve the algebraic equations. The post-processor provides for visualization of the results and includes the capability to display the geometry/mesh, create vector, contour, and 2D and 3D surface plots. Particles can be tracked throughout a simulation, and the model can be manipulated (i.e. changed by scaling, rotating, etc.), and all in full colored animated graphics.

Table 1: Design specification for EGR

Parameters	EGR 1
No. of tubes	28
No. of baffles	3
Tube length	180
Total length	230
Inlet coolant side diameter	19.5
Outlet coolant side diameter	19.5
Inlet exhaust side diameter	30
Outlet exhaust side diameter	30

Table 2: Engine specification for CRDI engine

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

Data Reduction

The parameters which were of key interest were outlet temperature, outlet pressure, velocity outlet. 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

$A = Q / Uo * \Delta Tm$

Logarithmic temperature difference can becalculated as :

$\Delta T2 = Th1 - Tc2$

$\Delta T2 = Th2 - Tc1$

$\Delta Tm = \Delta T1 - \Delta T2 / \ln(\Delta T1\ \Delta T2)$

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:

$ho = ji * Cp * (ms/As) * (K/Cp*\mu s)^{(2/3)} * (\mu/\mu s*w)^{0.14}$

Tube side heat transfer coefficient can be calculated as:

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

The CAD model of EGR cooler is modeled using Creo 2 software which is sketch based; feature based parametric 3d modeling software developed by PTC.

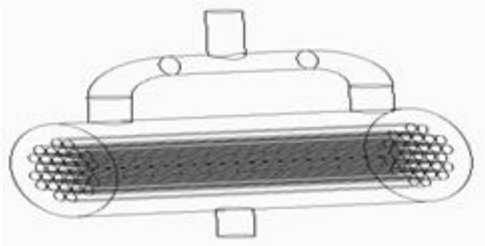

Figure 1.1: Double inlet configuration

Double inlet configuration is shown in fig 1.1 above has 2 inlets on both ends of shell. The coolant flow is divided in 2 parts on both sides.

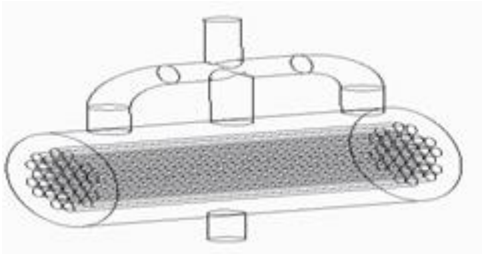

Figure 1.2: Triple inlet configuration

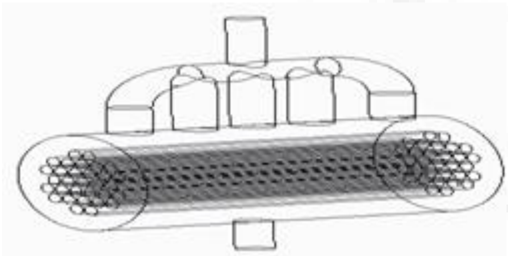

Figure 1.3: Five inlet configuration

5. Results and Discussion

The CFD analysis conducted on EGR cooler with single entry and multiple entry is simulated and contour plot of temperature, pressure and velocity are plotted as shown in section below. As engine works at different RPM thereby resulting in different emission gas temperatures. To analyze the cooling of EGR cooler different operating temperatures has been taken viz 419 ^{0}C ,589 ^{0}C,688 ^{0}C, 786.2^{0}C.

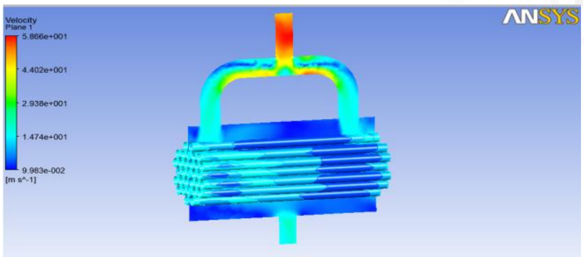

Figure 7: Velocity plot for 1st design EGR cooler

The velocity contour along with mid-section plane is shown in fig 7 above. The flow pattern shows that coolant flow gets divided in both directions to enter shell. The velocity reduces as it enters secondary inlet tubes shown by light blue color. The pressure contour along with mid-section plane is shown in fig 8. The coolant flow is directed perpendicular to pipe resulting in pressure built up shown by red and yellow contours with highest magnitude. The flow is then directed on secondary inlet tubes on both sides where pressure reduces considerable and achieves stagnancy as it enters shell.

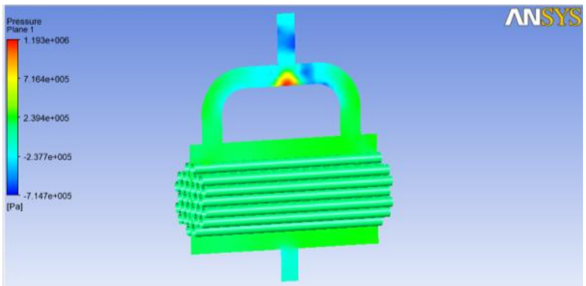

Figure 8: Pressure plot for 1st design EGR cooler

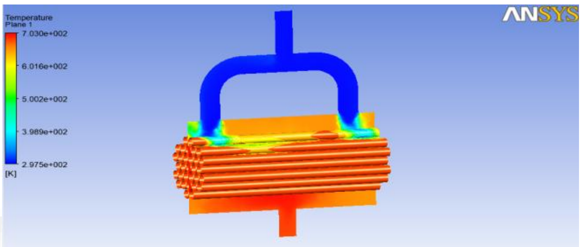

Figure 9: Temperature plot for 1st design EGR cooler

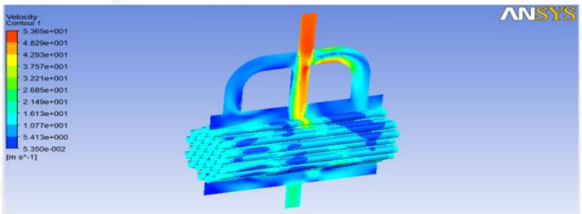

Figure 10: Velocity plot for 2nd design EGR cooler

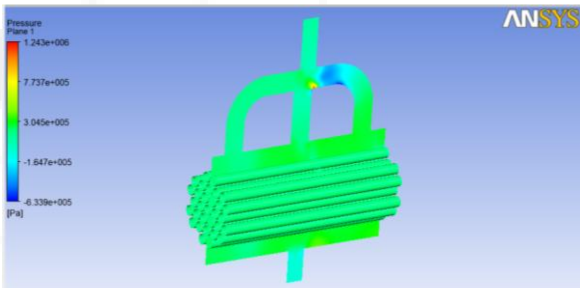

Figure 11: Pressure plot for 2nd design EGR cooler

The velocity plot shown in fig 10 shows the highest magnitude along central tube shown by dark red color and lower magnitude along other two pipes shown by light blue color. The pressure contour shown in fig 11 shows higher magnitude at corner.

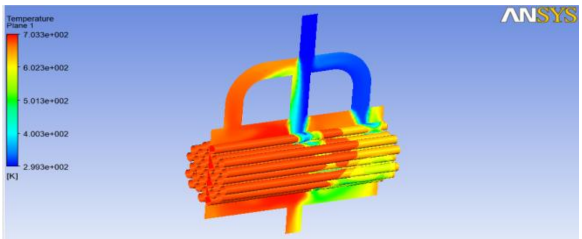

Figure 12: Temperature plot for 2nd design EGR cooler

The temperature plot shown in fig 11 above shows lower cooling effect on first half of shell volume and cooling is due to mid tube and side tube only. The cooling effect is non-uniform and lesser.

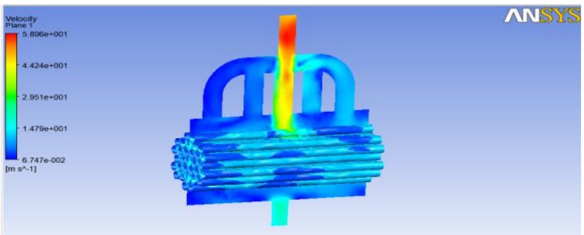

Figure 13: Velocity plot for 2nd design EGR cooler

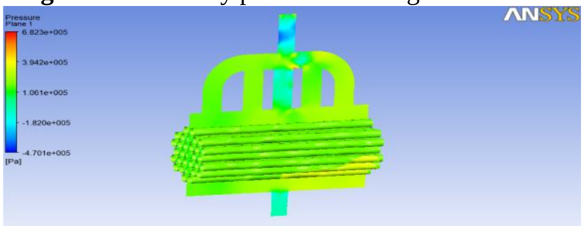

Figure 14: Pressure plot for 3rd design EGR cooler

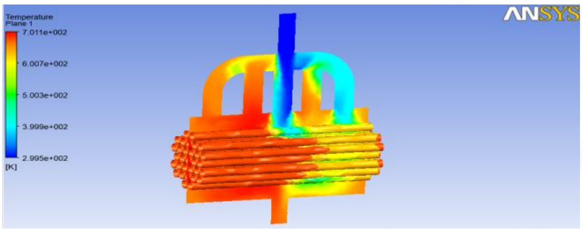

Figure 15: Temperature plot for 3rd design EGR cooler

The velocity plot, pressure plot and temperature plot as in figures above for 3rd design shows similar trends as of 2nd design resulting in non-uniform cooling effect and non-uniform flow along different inlet flow tubes. Improvement in heat transfer is not achieved using 3 and 5 inlet configurations for shell as turbulence required for heat transfer is not generated with 3 inlet and 5 inlet configurations.

Table 3: Temperature table for double entry EGR cooler design

Gas in Temp (K)	692.92	862.85	961.05	1059.26
Gas Out Temp (K)	352	473	543	680
Coolant in Temp (K)	341	341	341	341
Coolant Out Temp (K)	346	347	348	350

Table 4: Temperature table for three inlet entry EGR cooler design

Gas in Temp (K)	692.92	862.85	961.05	1059.26
Gas Out Temp (K)	374	485	569	701
Coolant in Temp (K)	341	341	341	341
Coolant Out Temp (K)	348	346	344	348

Table 5: Temperature table for five inlet entry EGR cooler design

Gas in Temp (K)	692.92	862.85	961.05	1059.26
Gas Out Temp (K)	372	481	564	697
Coolant in Temp (K)	341	341	341	341
Coolant Out Temp (K)	349	347	346	350

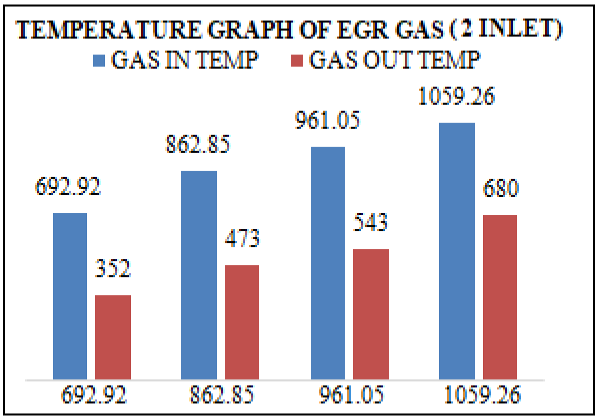

Figure 16: Temperature plot for 2 inlet design EGR cooler

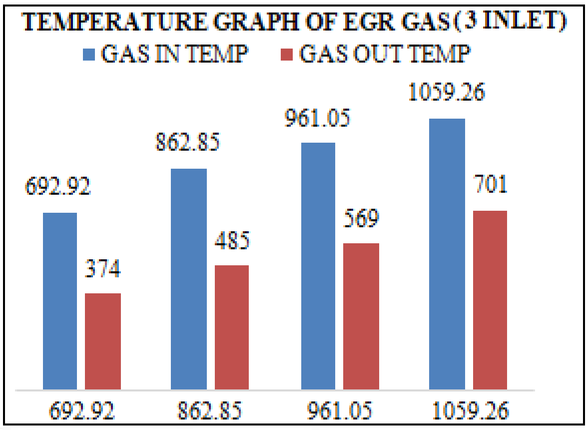

Figure 17: Temperature plot for 3inlet design EGR cooler

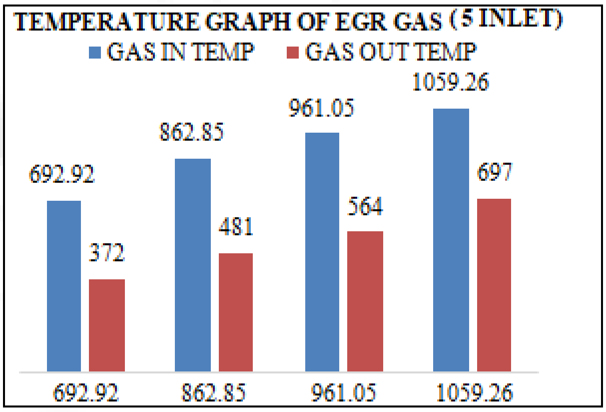

Figure 18: Temperature plot for 3inlet design EGR cooler

6. Conclusion

Three designs of EGR cooler are analyzed using ANSYS CFX under same operating conditions. First design is based on double inlet entry of coolant while second design is based on three inlet entry of coolant and third has five inlet entry in EGR cooler. It has been found EGR cooler with two inlets for coolant performs better in terms of cooling effectiveness as compared to other two designs. This could be attributed to better fluid flow characteristics specially turbulence achieved in design with two inlets which lowers gas temperature in higher magnitude as compared to other two designs, therefore has greater effectiveness and better heat transfer rate.

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