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Optimization of an Exhaust Gas Recirculation Cooler using CFD Technique

Duraisamy S., Bhaleghare Santosh S., Sundaralingam S., Thundil Karuppa Raj R. and Elango T.
School of Mechanical and Building Sciences, VIT University, Vellore-632014, TN, INDIA

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Abstract

Presently exhaust emission regulation for automobile engines are being too much strengthened worldwide. In order to comply with modern pollution control norms exhaust gas recirculation (EGR) system is recognized as one of most potential techniques to reduce NOx. EGR cooler is one of the important components in EGR system. This study represents the methodology to optimize EGR cooler based on numerical techniques using computational fluid dynamics (CFD) tools. The EGR cooler performance highly depends on the design, shape and size of the cooler tubes and diffuser. By optimizing the size and the shape of the diffuser it is possible to increase the effectiveness of the EGR cooler. The flow and the heat distribution will be analyzed for the optimized geometry of the EGR cooler. The pre-processing work and post processing is carried out using STAR CCM+. The governing equations conservation of mass, momentum and energy are solved.

Keywords: EGR, EGR cooler, pollution control norms.

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 performances[1,2].

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[3]. A multi-tube EGR cooler was developed to have high heat exchanger efficiency with high reliability for heavy-duty diesel engine application.

EGR is helpful in NOx reduction while limiting the penalties in terms of particulate emission and BSFC. The EGR cooler uses engine coolant for cooling the exhaust gas. The EGR cooled gas temperature should be as low as possible to avoid temperature raise. Latest technologies are being developed focusing on achieving better heat transfer between exhaust gas and coolant. This can be achieved by proper design of diffuser, flow pattern, multi-tubes etc. The tube used is generally straight with smooth surface. However heat transfer is relatively low. To achieve heat exchanger efficiency, the tube length should be long. When coolant doesn't flow efficiently inside shell of EGR, the heat transfer in the shell may not occur properly.

The effective shape of diffuser increases the heat transfer rate. The function of the diffuser is to distribute the flow into the tubes and collect cooled gases from output. For better heat transfer prolong shell and tube with counter flow is studied. The EGR cooler consist of two bundles for airflow and surrounded by big tube for coolant flow. Each tube bundle of air has small tubes of 70 numbers. The tube has a dimension of 6.4 mm inner diameter and 7mm outer diameter. The diffuser will be attached at the end of the direct flow of air in and out of the cooler.

Diffuser design should make the gas flow into tubes as equally as possible and with minimal possible pressure drop. The aim is to evaluate the diffuser design in terms of flow efficiency. The single tube cooler experimental setup is made for validation purpose with numerical predictions.

Design Parameters: The design involves design of diffuser and tube bundle: i. Diffuser-various shapes have been analyzed, ii. Tube Bundles- Varying the tube bundle size.

Governing Equations: All of the CFD, in one form or another, is based on the fundamental governing equations of fluid dynamics – the continuity, momentum, and energy equations. This equation speaks physics. Each model of flow directly produces a different mathematical statement of the governing equations. After the equations are obtained, forms particularly suited for use in CFD solutions will be delineated[5].

These equations (1)-(5) shown below are solved in this study.
Conservation of mass

$$\nabla.(\rho\vec{V}) = 0 \quad (1)$$

Conservation of energy

$$\nabla.(\rho e\vec{V}) = -p\nabla.\vec{V} + \nabla.(K\nabla T) + q + \phi \quad (2)$$

Conservation of momentum

$$x\text{-momentum}: \nabla.(\rho u\vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \quad (3)$$

$$y\text{-momentum}: \nabla.(\rho u\vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho g \quad (4)$$

$$z\text{-momentum}: \nabla.(\rho u\vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \quad (5)$$

Methodology

In real practice, EGR cooler consists of 78 cooler tubes. In order to validate the numerical results, the experiment is carried out on single tube test rig since single tube result is sufficient to validate the result and to avoid the complication of doing experiment on 78 tube test rig.

The setup consists of single tube cross flow heat exchanger. It consists of two concentric tubes of copper for better heat transfer phenomenon. The dimensions of the tubes are 25 mm inner diameter and 51 mm outer diameter. The tubes are of 500 mm length. The inner tube is for air flow and outer tube is for water flow. The thermocouples are attached at six locations for air in the working length. Similarly thermocouples are attached at various locations as shown in figure 1 for measuring water temperature along the length of the shell and tube heat exchanger.

The thermocouples are placed on central line of tube to measure the variation of temperature along the length. The water flow made to flow against gravitation for better cooling effect. The constant hot air flow is obtained by using heater and blower setup as shown in circuit figure 2.

The Rheostat is used to control the current flowing to heater by varying the resistance so that the heating capacity of heater and temperature of the inlet air is controlled. By maintaining the hot air inlet temperature at 74°C, the variation of temperature along the length of tube is measured using thermocouple and the datas are observed in multiple indicator figure 3.

Numerical Simulation: Computational fluid dynamics has been used to determine the flow patterns, temperature distribution along the length of the shell and tube heat exchanger. The software used for the simulation is Star CCM+. The solvers are of segregated type and employs Standard k-ε turbulence model of closure. Reynolds Averaged Navier stokes equation is used to determine the mean velocity components. The flow considered for the analysis is 3 dimensional steady state flows.

Geometry Modelling: The single tube EGR cooler is modeled using CATIA V5R17 and then validated using STAR CCM+. The 2D sketch of the model is given below. The modeling is done as a single tube cooler figure 4.

Geometry of EGR Cooler: The above shown EGR cooler consist of 78 tubes. The EGR cooler taken is a shell and tube heat exchanger with a trumpet diffuser. The flow is cross flow. Different types of diffuser designs are studied. Diffuser is used to reduce the flow velocity and to enhance the heat characteristics near the wall figure 5.

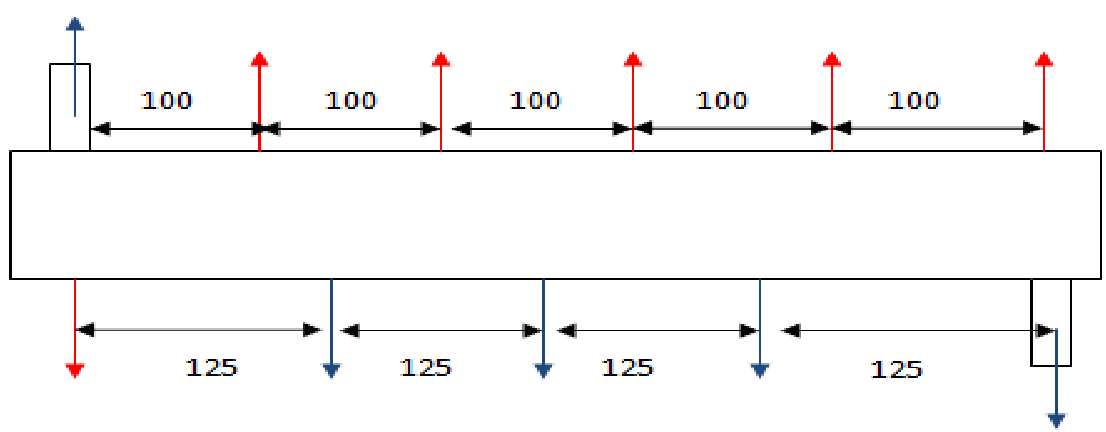

Figure-1
Locations of Thermocouple (All dimensions are in mm)

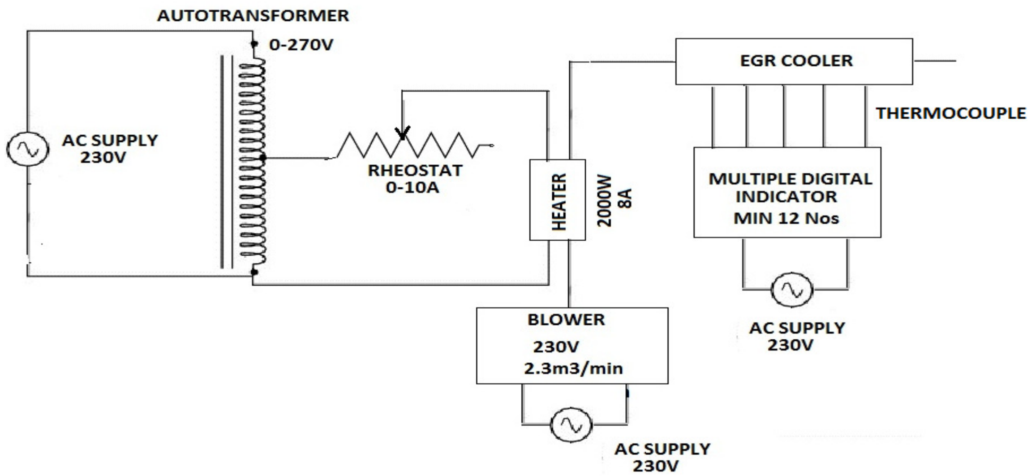

Figure 2
Circuit Diagram

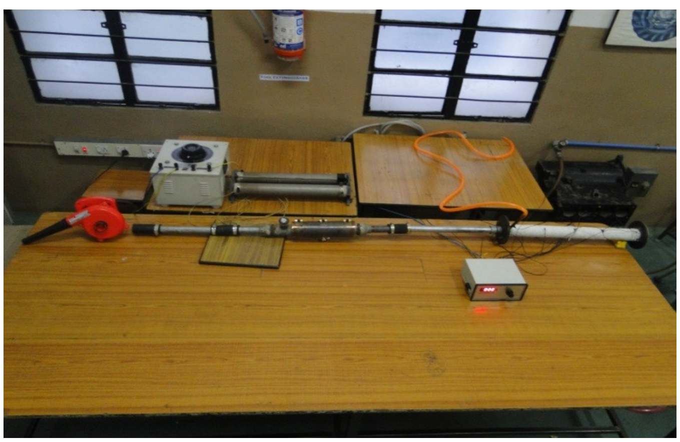

Figure 3
Experimental setup for a single tube EGR cooler

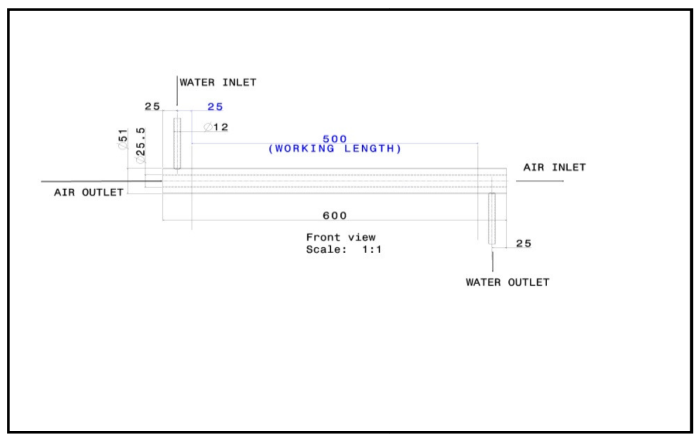

Figure 4
Sketch of Single tube EGR cooler

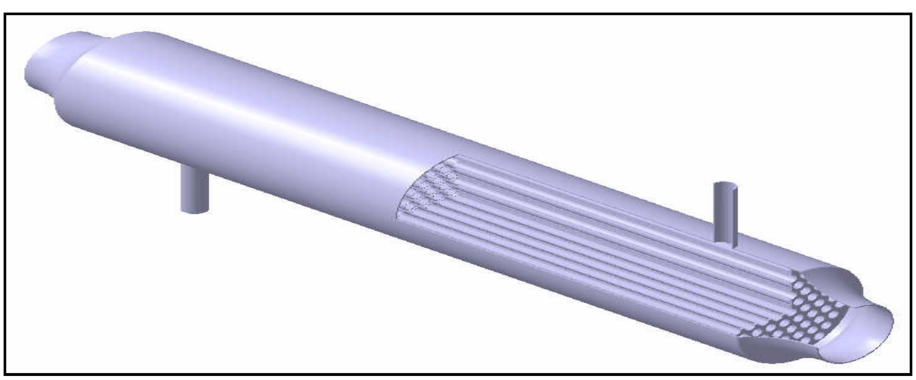

Figure 5
EGR cooler CAD model

Boundary Conditions: The boundary conditions for the single shell and tube heat exchanger is as listed in below table 1.

Table 1
Boundary Conditions

Parameter	
Inlet Air temperature (degrees)	74
Inlet water temperature (degrees)	34
Material Used	Copper
Air inlet mass flow rate (kg/s)	0.04916
Water Inlet mass flow rate (kg/s)	0.00747

Meshing: The shell and tube heat exchanger is divided into three regions: i. Air domain, ii. Water domain, iii. Solid domain

The meshing is done using polyhedral mesh for the fluid domain and with embedded-thin mesh for the solid region. The velocity and thermal boundary layers are captured in the fluid region by growing prism layer meshes. The mesh contains no free edges and non-manifold edges: air: 34281 cells, 194156 faces, coolant: 111492 cells, 615671 faces, solid: 69213 cells, 241681 faces

Results and Discussion

The numerical study is validated by the single tube cooler experimental setup. The comparison between experiments and corresponding numerical simulations are presented for the single tube cooler and the error percentage for the same is calculated.

Single Tube Cooler: The plot below shows the temperature variation along the central line of the single tube cooler. The results of the experiment agree with the observed values with 97 % accuracy figure 7.

The air temperature in the observed reading is found to be almost similar to that of experimental values and the percentage error is shown in table 2.

Table 2
Error Percentage

Readings	**% error = (Experimental - Observed)/Experimental *100**
1	0
2	6.849315
3	4.225352
4	5.633803
5	-4.7619

The absolute average error is found to be around 4%.

The water temperature in the observed reading is found to be similar to that of experimental values and the percentage error is shown in table 3.

Table 3
Error Percentage

Readings	**% error = (Experimental - Observed)/Experimental *100**
1	0
2	2.702703
3	0
4	0
5	-2.63158

The absolute average error in found to be around 1.1%.

From the contour plot the temperature variations seems to be fair as per experimental results. There is better heat transfer along the radial distance of the single tube cooler as expected. The top of the cooler seems to have more temperature than the lower end as predicted.

The Conservation of mass, energy and momentum are solved with a residual value of E-6.The differential equations converges to a good solution after 532 iterations.

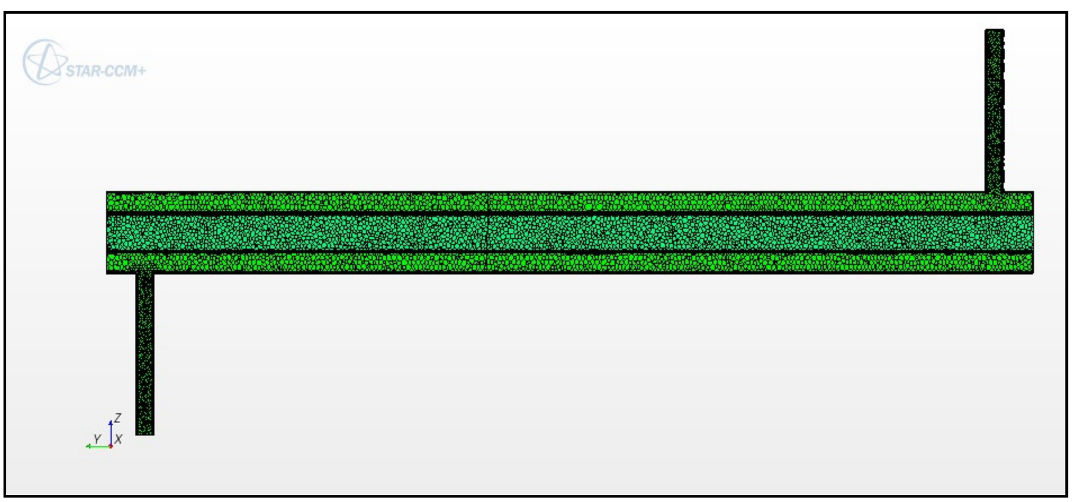

Figure 6
Meshed single tube EGR cooler

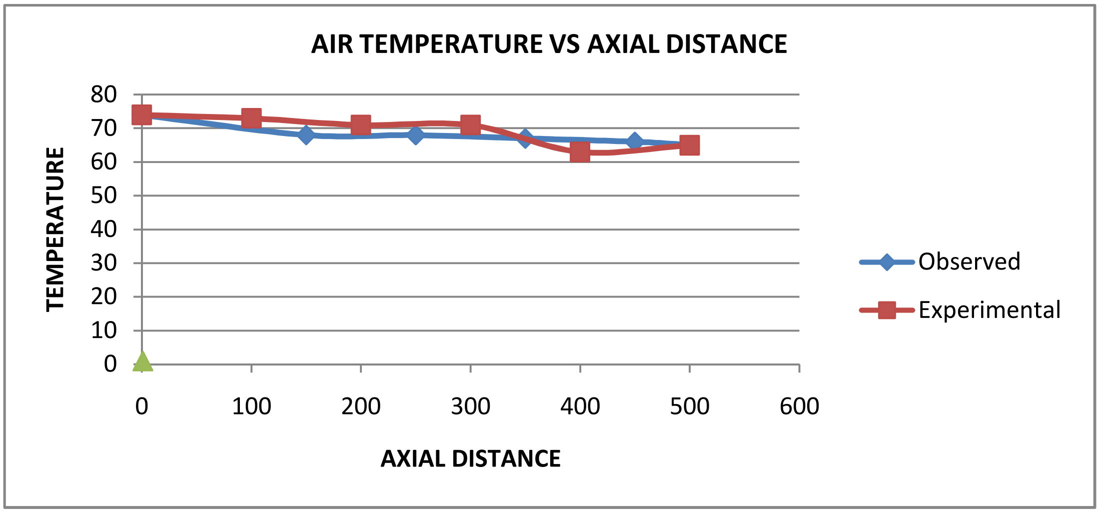

Figure 7
Axial distance Vs temperature

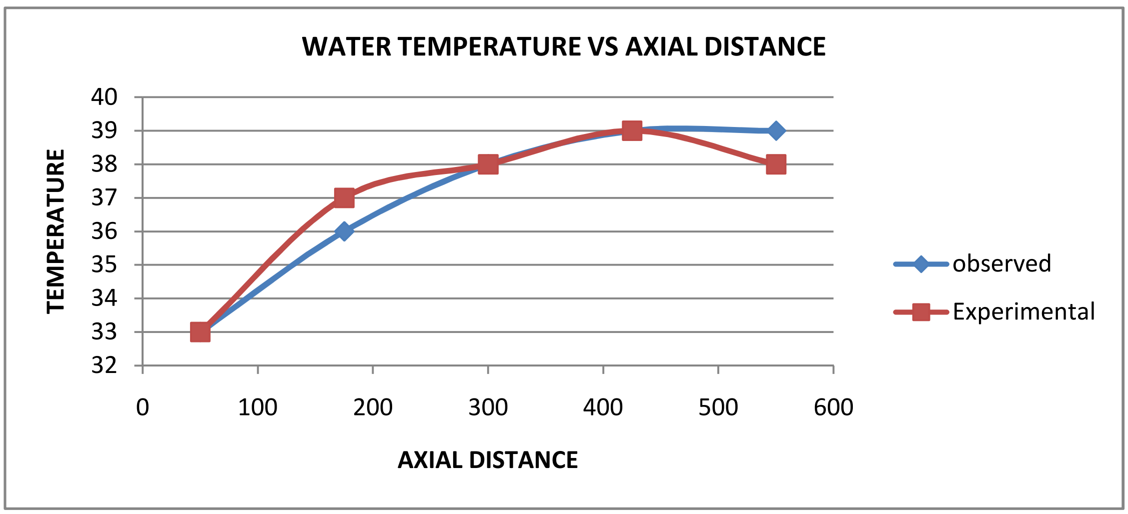

Figure 8
Axial distance Vs temperature

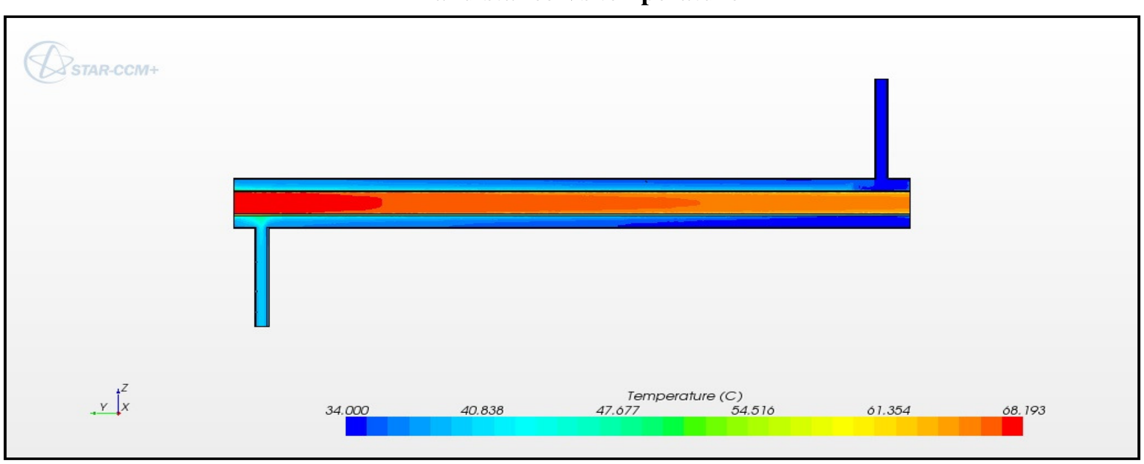

Figure 9
Temperature Contour

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Conclusion

The experiment for the single tube EGR cooler is done. Experimental results have a good agreement with the CFD results. Further the effect of diffuser shape, size and number of the tubes on the EGR cooler performance can be extended to configure the real time EGR cooler. Thus this study provides an benchmark platform to analyze numerically the EGR cooler performance.

Symbols a Notations: P = pressure (Pascal), g = acceleration due to gravity (m/s^2), V = Velocity of the fluid (m/s^2), τ = Stress (N/m^2), ϱ = Density of the fluid (kg/m^3)

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