ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 1.852

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Thermal analysis of baffled shell and tube type EGR cooler for different types of tubes using CFD

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Abstract

Exhaust Gas Recirculation (EGR) technique using EGR cooler reduces the NO_x content from the tailpipe emission of Diesel engines. Commercial computational fluid dynamics (CFD) code is used to solve and simulate the flow-fields and temperature distribution of fluids inside the EGR cooler. In this investigation two models (model-a and model-b) of EGR coolers are developed using Pro/Engineer Wildfire 4.0 software. Model-a is a single pass baffled shell and tube heat exchanger with staggered tube arrangement of plain tubes and having conical shaped stationary heads (gas inlet/outlet chamber) [2]. Model-b is having the same tube arrangement and spacing as they were in model-a, but the plain tubes were replaced with internally finned tubes to increase the internal surface area of tubes. The finned tubes are of same outer diameter and same tube material as that of plain tubes. In model-a and model-b, the inlet conditions of both the cooling water and hot gases are the same. These models are analysed with Ansys Fluent 13.0 software. The CFD results show that, by replacing the plain tubes with internally finned tubes, the rate of heat exchange between the cooling water and hot gases enhanced.

Keywords: Exhaust gas recirculation (EGR) cooler, Computational Fluid Dynamics (CFD), Baffled shell and tube EGR cooler, plain tubes and internally finned tubes.

Introduction

Diesel engines are typically characterized by low fuel consumption and very low CO_2 emissions. In the beginning they were used in power tractors and heavy trucks, but now they increasingly used in smaller trucks and passenger cars due to their low fuel consumption. However, from a pollution aspect, the high NOx emission from the diesel engine remains a major problem (Kakoi et al., 1988; Park et al., 2003; McKinley, 1997) [6].

In recent years, stringent emissions legislation has been imposed worldwide on nitrogen oxide (NOx) and particulate matter (PM) emissions from diesel engines (Moon et al., 2006). With the development of strategies to accomplish the requirements of these legislations, improvements have been done and are still under progress [6].

So engines will have to undergo further development to comply with future emission limits. Recent success stories have demonstrated how a cooled exhaust gas recirculation (EGR) system can reduce NO_x emissions (McKinley, 1997; Lim et al., 2004). The limits discussed in connection with new emission legislation, such as EURO4, EURO5, EPA07, and EPA10, demand a high performance exhaust gas cooler (Leet et al., 2004; He et al., 2003) [6]. Exhaust gas recirculation (EGR) technique is recognized as one of the strategies evolved for reducing the emission of NO_x from diesel engines. In this technique a fraction of exhaust gases from the tailpipe exhaust is sent back to the combustion chamber along with the fresh charge. The recirculation of exhaust gas lowers the peak combustion temperatures inside combustion chamber below 2000K (1727ºC). The rate of formation of NO_x greatly depends on temperature, as nitrogen and oxygen do not react with each other at temperatures below 2000K [8]. Thus EGR reduces the NO_x in emissions of diesel engine [1]. EGR technique is more effective when the hot exhaust gas is cooled before it enters in the combustion chamber. Cooling of exhaust gases is done by using EGR cooler, which is a heat exchanger. Many designs of heat exchanger as EGR cooler have been proposed and are in use. The design for EGR cooler should be the most feasible one i.e. a compact design with good effectiveness, durable in high temperatures and corrosion or erosion resistant. It should be easy to clean as well [7]. So we have proposed a baffled shell and tube heat exchanger which is designed using "Kern's method" [4] and used to cool exhaust gases.

This paper deals primarily with the thermal analysis of EGR coolers. We have performed simulation through CFD analysis to determine how the internal shape of EGR cooler tubes affects its efficiency. The flow behaviour of fluids moving inside this heat exchanger is simulated, analysed and compared for different tube arrangements of proposed EGR coolers. ANSYS FLUENT 13.0 solver is used for this analysis. This comparative analysis can be useful while selecting most feasible design of EGR cooler.

Materials and methods

Designing and Analysis

Most of the EGR coolers cool the hot exhaust gases coming out of the engine to a temperature around 100 to 175 °C. So we have taken the exit temperature of hot fluid about 150 °C for calculation purpose. Kern's method [4] and TEMA (Tubular Exchanger Manufacturers Association) handbook [2] are used to obtain various design features of required EGR cooler. These design features are summarised in Table-1.

Table-1: Design features of EGR cooler obtained using Kern's Method [4] and Tubular Exchanger Manufacturing Association (TEMA) handbook [2]

Outer diameter of tubes (d_o)	12.35 mm
Length of tubes	200 mm
Number of Tubes	6
Tube Thickness	1.2 mm
Tube inner diameter	9.95
Shell Diameter	50 mm

Model Description:

The EGR cooler is an assembly of two conical gas inlet/outlet chambers, four gaskets, six aluminium tubes in staggered arrangement, two tube-sheets, one shell and twelve nut and bolts. In this arrangement, the hot exhaust gas will flow through tube side and cooling water will flow from shell side, in opposite direction of hot gases as shown in fig-1.

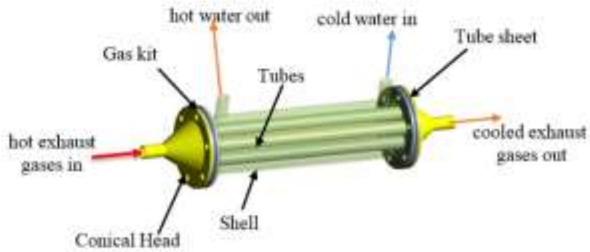

Fig-1: EGR Cooler Assembly

Model-a of this EGR cooler is designed with plain tubes. In model-b, the plain tubes of model-a are replaced with internally finned tubes (of same outer diameter and same tube material) to increase the internal surface area of tubes. These internal fins are straight and parallel to the tube axis. The rest of design configuration remains same.

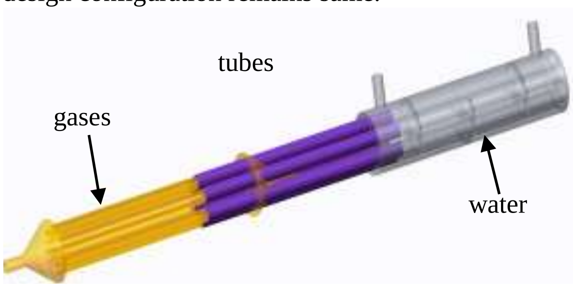

Fig-2: Fluid Model Assembly

Fig-2 shows the fluid volume which will be occupied by the hot gases and cooling water when they are inside EGR cooler. The gas part of this fluid model assembly will be varied when plain tubes are replaced with finned tubes [2]. So from analysis point of view, a separate fluid model for model-a and model-b is modelled using Pro/Engineer Wildfire 4.0.

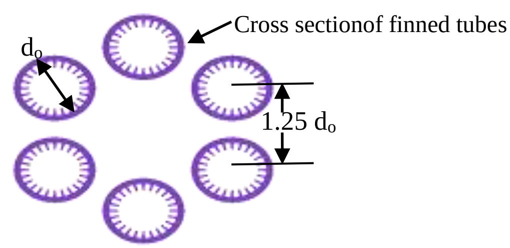

Fig-3: Tube arrangement and spacing

Fig-3 shows the arrangement and spacing of model-b with finned tubes in staggered configuration. In order to keep geometrical features of model-a and model-b identical, model-a is modelled with a similar configuration of plain tubes.

The analysis is carried out for similar thermal and flow conditions. Firstly the whole model is divided into very small regions called nodes and elements by Ansys Mesher tool, then Ansys Fluent

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
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13.0 solver is used for computation and simulation of variation in temperature at different zones.

Boundary Conditions

Experimental investigations conducted on Diesel-engine test rig at institute laboratory revealed the boundary conditions which will be entered in Ansys Fluent Solver Setup for the analysis of EGR cooler. These boundary conditions are displayed in table-2.

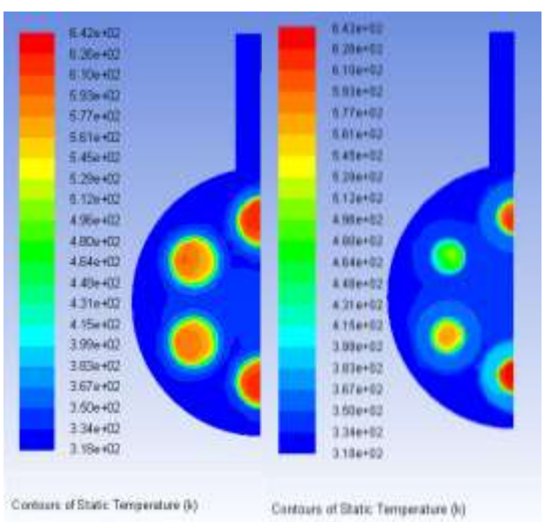
Table-2: Operating temperatures from Experiment

Material/ Property	Cooling water	Exhaust gases
Mass flow Rate (kg/sec)	**0.01**	**0.002**
Inlet Temperature	**45 °C (318K)**	**369 °C (642 K)**

Results and discussion

CFD Results: Contours of Temperature for different sections

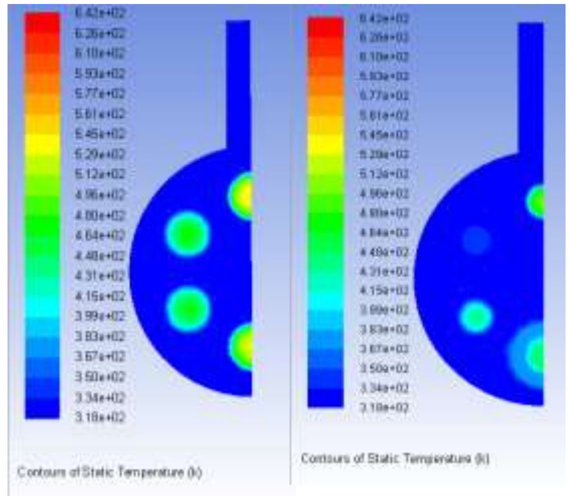
The temperature contours shows the variation in temperature of hot gases flowing inside different tubes along with the variation of temperature of cold water surrounding the tubes for a defined section of the EGR Cooler. The variation of colour from blue to red is shown in a scale with increase in temperatures in a direction from blue colour to red colour and vice versa. The temperature at any point can be measured in Kelvins by matching the colour at that point to the colour of scale.



Model-a *Model-b*

Fig-4: at symmtry of water inlet

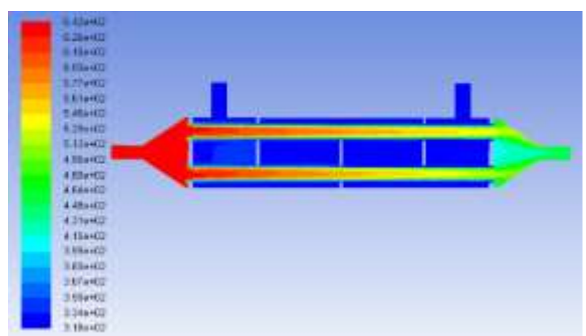
Fig-4 shows the comparison of temperature contours at the section of outlet water.



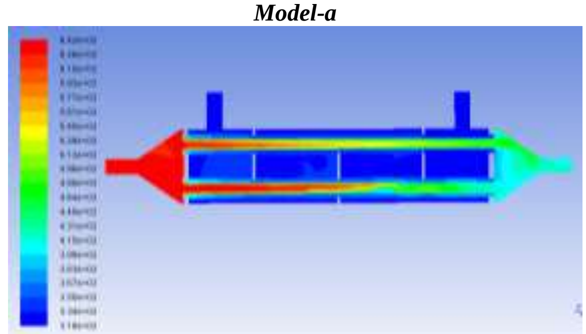
Model-a *Model-b*

Fig-5: at water outlet symmetry

Fig-5 shows the comparison of temperature contours at the section of inlet water. From fig-4 and fig-5, it is observed that the temperature drop of hot gases at the exit of model-a is less than model-b. This is because internal surface area of plain tubes used in model-a is less than model-b. So heat gained by finned tubes of model-b is more in the flow zone of hot gases.



Model-a



Model-b

Fig-6: at shell-symmetry

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
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The comparison of temperature contours (of two fluids) at the overall symmetry of EGR Cooler for both the models is shown in fig-6. The results of temperature contours shows that average exit temperature of hot gases for model-b is less than model-a which is shown in table-3.

Table 3: CFD Results for temperatures at different zones of Model-a and Model-b

Parameter	Model-a		Model-b	
	Inlet Section	Outlet Section	Inlet Section	Outlet Section
Mean Temp. of exhaust gas (°C)	369.0	165.734	369.0	140.871
Mean Temp. of water (°C)	45.0	55.576	45.0	56.73
Effectiveness (ε)	62.73%		70.41%	

We have found that the effectiveness of model-b is higher than model-a.

Formulae/Expressions:

Effectiveness (ε) [3]

$$\varepsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})} \quad (1)$$

Conclusion

The conventional methods for testing the performance of a shell and tube EGR cooler are very expensive and time consuming. The present study show that CFD analysis technique is very effective in saving the cost and time associated with the experimental methods of predicting the performance of a proposed design.

Thus CFD is very important tool for the design and development of baffled shell and tube EGR cooler as it eliminates the time and cost in developing the prototype of proposed design and its testing.

It is seen that how the use of finned tubes improves the effectiveness of EGR cooler when they replace the conventional plain tubes. Plain tubes used in model-a have less surface area than finned tubes used in model-b. So, tubes of model-b extracts more heat from hot exhaust gases as compared to tubes of model-a. This enhanced the heat exchange in model-b and the effectiveness of model-b is increased by 7.68%.

Absence of experimental results for the feasibility of proposed design is the limitation of this study. An experimental investigation shall be conducted in future for a fabricated model based on the proposed design and its results shall be compared with CFD analysis results.

Acknowledgements

We are thankful to Medi-Caps Institute of Technology and Management, Indore, M.P., India for providing technical assistance in CFD work with ANSYS FLUENT 13.0.

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Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 1.852

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