CFD Simulation of Stack Type EGR Cooler for CI Engine
Mr. Ibrahim H. Shah¹ Raghvendra S. Bhadoriya²
¹²Assistant Professor ²PG Student
1,2Department of Mechanical Engineering
Institute of Engineering and Technology DAVV, Indore- 452017, MP (India)

Abstract— The EGR (exhaust gas recirculation) technique can greatly reduce the NOx emission of diesel engines, especially when an EGR cooler is employed. Numerical simulations are applied to study the flow field and temperature distributions inside the EGR cooler. Three different models of EGR cooler are investigated, among which model A is a traditional one shell and tube while models B is stack type. In models C fins are added in stack type geometry. The results show that the heat exchange of the stack-type EGR cooler is much more effective than that of the shell and tube type because of the increased surface area. In conclusion we suggest that the improved structures are more powerful than the traditional one.

Key words: Exhaust Gas Recirculation (EGR) Cooler, Computational Fluid Dynamics (CFD), Shell and Tube Heat Exchanger, Stack Type Heat Exchanger

I. INTRODUCTION

Diesel engines are the primary power source of vehicles used in heavy duty applications. [5] The heavy duty engine includes buses, large trucks, and off-highway construction and mining equipment’s. Furthermore, diesel engines are winning an increasing share of the light duty vehicle market worldwide. The popularity of the diesel engine revolves around its fuel efficiency, reliability, and durability. High compression ratios along with relatively high-oxygen concentrations in the diesel combustion chambers are responsible for the good fuel efficiency and low CO and hydrocarbon emissions when compared to a gasoline engine. [4] The CO present in residual gas in diesel engine is also less compared with petrol engine. However, these same factors result in high NOx emissions. The various sources of NOx emission to the atmosphere are motor vehicles (49%), electric utilities (25%) and other commercial and residential sources that burns fuel (19%). The main pollutants from diesel engines are NO and particulate matter (PM) [3]. The exhaust gases from the automotive engines is a mixture of unburnt fuel (Hydrocarbon), the product of partial combustion (Hydrocarbon, particulate matter and carbon monoxide), the product of complete combustion (Carbon dioxide and water vapour), products of high temperatures and pressures generated during combustion (oxides of nitrogen) and the elements of the inlet air that undergo no change during combustion (nitrogen, oxygen, carbon dioxide and water vapour). The components of the exhaust gas mixture which are hazardous to the human life and environment are hydrocarbons, oxides of nitrogen, carbon monoxide and particulate matter [13]. Due to outstanding performance of stack type heat exchanger they have been introduced into the EGR cooler recently [6]. Past research focused on either experimentation with different geometric design or comparative analysis between measured results and evaluation. In the present research three design models based on EGR coolers are presented. Commercial computational fluid dynamics (CFD) [9] codes based upon the finite volume method is used to make the simulation. Then the numerical Results are tabulated and compared. The flow mechanism and temperature fields inside EGR cooler are analyzed to explain the optimized phenomenon in the heat exchanger [11]. More effective EGR cooler more amount of exhaust gas can be sent into combustion chamber and adiabatic flame reduces which result in less NOx formation [10]. Flow characteristic in plate type heat exchanger is steadier but increase area cause more heat exchange [12].

II. MODEL DESCRIPTION

A. Engine Description

The engine for which we decide to design effective EGR cooler was 1248cc, turbocharged 75ps@4000 rpm, maximum torque 190kgf-m@2000 rpm with compression ratio of 17.7. All the theoretical calculation of engine were done and mass flow rate, exhaust gas temperature which is supposed to enter in EGR cooler as inlet are obtained. At 20% EGR Inlet hot gas mass flow rate = 0.005 Kg/s and temperature of exhaust gas is 963K.

All the operating conditions are listed in table 1. For the operating parameters we design different model of EGR cooler by considering TEMA standards and ‘ε-NTU method’ [2]. Ansys Fluent 15.0 solver is used to simulate the temperature contours, pressure contours, and velocity vectors of fluid flow. As operating condition were kept same for all the models.


<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Density (kg/m³)</td>
<td>0.35</td>
<td>990.1</td>
</tr>
<tr>
<td>2.</td>
<td>Thermal conductivity (W/m-K)</td>
<td>0.065</td>
<td>0.637</td>
</tr>
<tr>
<td>3.</td>
<td>Viscosity (Kg/m-s)</td>
<td>4.15 x 10⁻⁵</td>
<td>0.596 x 10⁻³</td>
</tr>
<tr>
<td>4.</td>
<td>Prandtl Number</td>
<td>0.714</td>
<td>3.91</td>
</tr>
<tr>
<td>5.</td>
<td>Mass flow rate (Kg/sec)</td>
<td>0.005</td>
<td>0.01</td>
</tr>
<tr>
<td>6.</td>
<td>Specific heat (KJ/Kg-K)</td>
<td>1132</td>
<td>4180</td>
</tr>
<tr>
<td>7.</td>
<td>Inlet Temperature (K)</td>
<td>963</td>
<td>318</td>
</tr>
</tbody>
</table>

Table 1: Operating Parameters

B. EGR Coolers Model Description

1) Model A
Model A is conventional shell and tube model with 13 tube of 9.6mm diameter, 11.875 mm triangular pitch and 0.865 mm thickness with length of 76 mm. As shown in figure 1.1(a) [15]

2) Model B
Stack-type cooler is the plate-fin heat exchanger and its overall core size is about 76x56 mm and length of 76mm. where 5 no of stack of 10mm x50 mm are inserted in shell with plane rectangular fin of thickness of 0.2 mm and 8 mm height. As shown in figure 1.1(b) [15]
3) Model C
Model C is like model B but the rectangular plane fin are replaced by wavy fin arrangement keeping the entire dimension same. As shown in figure 1.3(c).

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**Fig. 1.1(a):**

**Fig. 1.1(b):**

**Fig. 1.1(c):**

ANSYS fluent 15.0 solver is used to solve discretized Navier-stokes equation for heat conduction in stacks. Here in this we used k-ε turbulent model to calculate the high speed turbulent flow of two fluids flowing inside the heat exchanger and for the momentum, energy and turbulence equation second order upwind method in selected, as it has more accurate results.

There are some governing equations used by the solver are:

a) **Continuity Equation**
The continuity equation describes the conservation of mass and is written as in equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_1}{\partial x_1} + \frac{\partial \rho U_2}{\partial x_2} + \frac{\partial \rho U_3}{\partial x_3} = 0$$

b) **Momentum Equations (Navier-Stokes Equations)**
The momentum balance, also known as the Navier-Stokes equations, follows Newton’s second law: The change in momentum in all directions equals the sum of forces acting in those directions. There are two different kinds of forces acting on a finite volume element, surface forces and body forces. Surface forces include pressure and viscous forces and body forces include gravity, centrifugal and electromagnetic forces [14]. The momentum equation in tensor notation for a Newtonian fluid can be written as in equation.

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + g_i$$

c) **Energy Equation**
Energy is present in many forms in flow i.e. as kinetic energy due to the mass and velocity of the fluid, as thermal energy, and as chemically bounded energy. Thus the total energy can be defined as the sum of all these energies [14].

$$h = h_n + h_T + h_C + \phi$$

Where

- \(h_n\) = \(\frac{3}{2} \rho U_1 U_1\) Kinetic energy
- \(h_T\) = \(\sum_n \sum_m C_{p,n} \Delta T\) Thermal energy
- \(h_C\) = \(\sum_n \sum_m h_n\) Chemical energy
- \(\phi = g_i x_i\) Potential energy

d) **Turbulence Modeling**
The standard k-ε model is a semi-empirical one, which is based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). The Reynolds stresses are related to the mean velocity gradients on the basis of the Boussinesq hypothesis. k and ε are obtained from the following transport equations: [14]

For k,

$$\frac{\partial k}{\partial t} + (U_i) \frac{\partial k}{\partial x_i} = \nu_T \left[ \frac{\partial (U_i)}{\partial x_i} \frac{\partial (U_j)}{\partial x_j} \right] - \varepsilon$$

and for ε

$$\frac{\partial \varepsilon}{\partial t} + (U_i) \frac{\partial \varepsilon}{\partial x_i} = C_{et} \nu_T \varepsilon \left[ \frac{\partial (U_i)}{\partial x_i} \frac{\partial (U_j)}{\partial x_j} \right] - C_{t2} \frac{\varepsilon^2}{k}$$

The k and ε are coupled to the governing equations via the relation \(\nu_T = C_{nu} \frac{k^2}{\varepsilon}\)

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_nu</td>
<td>0.09</td>
</tr>
<tr>
<td>C_t1</td>
<td>1.44</td>
</tr>
<tr>
<td>C_t2</td>
<td>1.92</td>
</tr>
<tr>
<td>C_k</td>
<td>1.00</td>
</tr>
<tr>
<td>C_\varepsilon</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Table 2: Closure Coefficients for k-ε Model
The empirical constant for the turbulent model is assigned in accordance with the recommendation of [16].

After solving the model in Ansys fluent solver temperature contours are obtained and result is tabulated in table 3.

**Fig. 1.2(a):** Temperature contour of MODEL A
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The conventional methods for testing the performance of an EGR cooler are very expensive and time consuming. The present study reveals that CFD analysis techniques are effective in cost and time saving in predicting the performance of proposed design. The present study deals with a CFD analysis for the flow structures and temperature distributions of the EGR cooler. The numerical results contribute to discover the inside flow and temperature field and it reveals the influence of the fins and novel inlet geometry. For the same operating conditions three models of EGR coolers are designed keeping same area and space constraints. Temperature change and pressure drop obtained and it is shown that stack type EGR cooler are more effective than conventional shell and tube and on varying the fins arrangements effectiveness increases more.

The limitation of the present study resides in the fact that there is no experimental evidence. Further investigation; such as model fabrication, experimentation and comparative analysis will be executed in future work.

REFERENCES
[3] Coulson & Richardson, Chemical Engineering Design

Table 3: Numerical Result of all the models

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Outlet Temperature of Exhaust Gas</th>
<th>Outlet Temperature of Coolant T_C0(K)</th>
<th>Pressure Drop (Pa)</th>
<th>Effectiveness (ε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>729.6</td>
<td>334.8</td>
<td>53</td>
<td>36.1%</td>
</tr>
<tr>
<td>B</td>
<td>678</td>
<td>338</td>
<td>83</td>
<td>44.1%</td>
</tr>
<tr>
<td>C</td>
<td>671</td>
<td>340</td>
<td>101</td>
<td>45.1%</td>
</tr>
</tbody>
</table>

Fig. 1.2(b): Temperature contour of MODEL B

Fig. 1.2(c): Temperature contour of MODEL C

III. CONCLUSION