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An optimization of comparative analysis to improve the effectiveness of EGR coolers used in diesel engine

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Abstract - *The EGR mechanism is the predominant method to reduce the emitted NO_x from diesel engine. The exhaust system reduces the combustion temperature, because of this formation of NO_x is reduced. Commercial computational fluid dynamics (CFD) is used to solve and simulate the flow-fields and temperature distribution of fluids inside the EGR cooler. There are three models of EGR coolers have been developed using Pro/engineer software. Model-a is a single pass shell and tube type heat exchanger with plain tubes having cylindrical shaped fixed head. Model-b is similar to the model-a except tubes because in model-b plain tubes were replaced with circular internally finned tubes to increase the surface area of tubes. In Model – c rectangular fins are used for analysis. In model-a, model-b and model - c the inlet conditions of both fluids kept constant for the analysis of effectiveness and exhaust temperature. Both analytical result and CFD result show that heat transfer between exhaust gas and coolant is increased for finned tubes. In three models rectangular fin tube model is more effective compared to other two models because surface area for heat transfer is more in rectangular fin tube model.*

Keywords- - *Exhaust gas recirculation (EGR) cooler, Effectiveness, Computational Fluid Dynamics (CFD), Finned tubes.*

I. INTRODUCTION

The harmful effect of NO_x emissions to health and environment is unavoidable, yet it can be reduced. There are several mechanisms to reduce the NO_x formation inside the combustion chamber of engine. EGR mechanism is one of them. Several researches show that to reduce the NO_x emissions lowering the combustion flame temperature is needed. This process is mostly completed by using a heat exchanger (shell and tube type heat exchanger) in which exhaust gas flows inside the tube and coolant flows inside the shell. The limits in connection with new emission legislation, such as EURO4, EURO5, EPA07, and EPA10, demand a high performance exhaust gas cooler. To meet these emission limits many designs of heat exchanger as EGR cooler have been proposed and are in use .

EGR system can be classified into different categories. Most important one of them is based on cooled or hot EGR. In cooled EGR, exhaust gas introduced to intake directly after being cooled down. Density and mass flow rate of intake charge is increased . Some characteristics of cooled EGR system are low NO_x, better knock suppression etc. on the other side, in the hot EGR, it will be recycled directly to intake.

In this paper we proposed a heat exchanger design with internal circular fins and rectangular fins. Doing so the heat transfer area of EGR cooler is increased and more heat transfer will take place between exhaust gas and coolant. The effectiveness of EGR cooler will be increased.

We have performed simulation through CFD analysis to determine how the internal shape of EGR cooler tubes affects its efficiency. The flow behavior of fluids moving inside this heat exchanger is simulated, analyzed and compared for different tube arrangements of proposed EGR coolers. ANSYS FLUENT 14.0 solver is used for this analysis. This comparative analysis can be useful while selecting most feasible design of EGR coolers.

II. MATERIALS AND METHODS

Design and analysis

In this paper an EGR cooler is designed with different types of fins like circular fin and rectangular fin for a particular diesel engine. Engine specification for that engine are given blow-

Description	Specification
Displacement	1248cc
Induction Type	Turbocharger
Bore x Stoke	69.6mmx82mm
Maximum power (ps/rpm)	75/4000
Compression ratio	17.7
EGR System	Cooled
Maximum torque(kgf-m/rpm)	190/2000

Table – 1 Engine specification

For given engine EGR cooler has following dimensions, outer diameter is 12mm, length of tubes 165mm, number of tubes 13, Tube thickness is 1mm and shell diameter is 70mm. In this EGR cooler rectangular and circular fins are attached inside the tube. Hot exhaust gases are flowing through tubes and coolant is flowing inside the shell.

III. BOUNDARY CONDITIONS

For a particular engine analytically boundary conditions have been calculated. These boundary conditions will be used in ANSYS Fluent Solver Setup for the analysis of EGR cooler. Boundary conditions are tabulated below in table-1

Material/ Property	**Cooling water**	**Exhaust gases**
Mass flow Rate (kg/sec)	**0.01**	**0.005**
Inlet Temperature	**50 °C (323K)**	**466 °C (739K)**

Table-2: Operating temperatures from analytical calculations

Effectiveness for the plain tube using NTU –method

Overall heat transfer coefficient U for gases is $70 W/m^2K$ [1]

Area of tubes
$A_s = 3.14 \times L \times d \times N_t = 0.067 m^2$

$NTU = UA/C_{min} = 1.031$

Effectiveness of counter flow EGR Cooler $\epsilon = \frac{(1-\exp(-NTU(1-R))}{(1-R\exp(-NTU(1-R))}$

After substituting the values $\epsilon = 61.1\%$
Kern's method to calculate the convective heat transfer coefficient of the tube side and shell side for the EGR cooler using triangular pitch pattern.

Tube side Reynolds number $= Re = 16797.01$
Nussett number $= Nu_t = .024\, Re^{.8} Pr^{.4}$
$Nu_t = 49.58$
Heat transfer coefficient $h_t = Nu\, k_t/d_i$
$h_t = 240.48 W/m^2\text{-}K$
Shell side Reynolds number

$Re = G_s d_e / \mu$
Re = 48619.36
$Nu_s = 1.04\ Re^{.4}\ Pr^{.3}$
$Nu_s = 117.3$
Shell side heat transfer coefficient (h_s)
$h_s = (Nu_s \times k_f)/d_e$
$h_s = 105.47\ W/m^2\text{-}K$

IV. CALCULATION FOR EGR COOLER WITH FINS

Effectiveness calculation for rectangular fins

Fins parameters for rectangular fins
Number of fins = 6
Fins height = 2.5mm
Fins width = 160mm
Fins thickness = 1mm

Surface area of rectangular fins

$A_s = P \times L$

Area of single fin = 800 mm^2

Total surface area of fins

$A_f = 4.8 \times 10^{-3} m^2$

Total unfinned area = tube area – area of fins

$= 5.071 \times 10^{-3}\ m^2$

Heat transferred from finned portion

$Q_f = h.A.(T_o - T_s)$

$Q_f = 480.03$ W
Heat transferred from unfinned area
$Q_{uf} = h.A.(T_o - T_s)$
Heat transferred from bared tube

$Q_b = hA(T_0 - T_s)$

$Q_b = 603.22$W
Now increase in heat transferred
$= \frac{(Q_f - Q_b)}{Q_b} \times 100$
= 63.6 %
Now calculating exhaust temperature of exhaust gases
$Q = mc_p(T_{in} - T_o)$
$T_o = 431.7$K
Now effectiveness of EGR cooler with longitudinal fins
Effectiveness $\epsilon = 73.2\%$

Now EGR cooler effectiveness with circular fins

Parameters of circular fins
Number of fins = 10
Spacing of fins = 16mm
Tube radius = 6mm
Inner radius with fins = 4mm
Surface area of circular fins

$A_f = 2\pi \times (_{R1}{}^2 - {}_{R2}{}^2) \times N_{fins}$

$A_f = 1.256 \times 10^{-3}\ m^2$

Unfinned area of tube = pipe surface area – number of fins x cross section area of fins
= 2π x r_1 x h - N_{fins} x 2π x r_1 x t
= 5. 277 x$10^{-3}m^2$
Now heat transfer rate of fins

Q_f= h.A. (T_o - T_s)

Q_f = 125.6 W
Heat transferred from unfinned area
Q_{uf} = hA (T_o - T_s)
Q_{uf}= 527. 8 W
Heat transferred from bare tube
Q_b= 603.22W

Increase in heat transferred = 8.32%

Total heat transfer rate with circular fins
Q_t= 1515.39W
Exhaust temperature of EGR cooler with circular fins
T_o = 458.37K
Effectiveness of EGR cooler with circular fins
ϵ = 67.4%

V. DESCRIPTION OF MODEL

In fig.1 assembly of the EGR cooler is shown. EGR cooler consists of 13 aluminum tubes, two tube sheets, one shell, two cylindrical gas inlet/outlet chamber and all this parts are assembled with help of twelve nuts and bolts. In this arrangement both fluid flow in opposite direction.

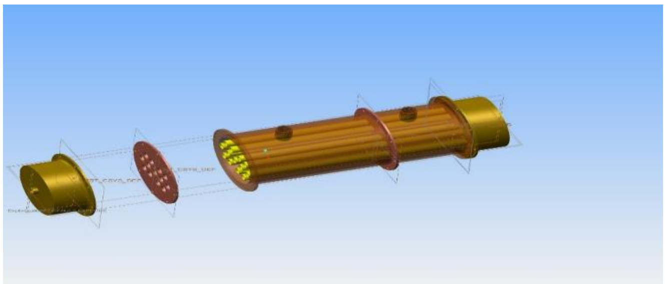

Fig.1Assembly of EGR cooler

Model – a consist of plain tube, model – b consist of internal circular fin tube and model – c consist of internal rectangular fin tube. Tubes of model – b and model – c are made of same material as model – a. In model – b circular fins are attached to the tubes in transverse direction of the tube to increase the surface area. In model – c rectangular fins are attached in longitudinal direction of the tube so that surface area can be increased for the heat transfer. Remaining design of the model – b and model – c is same.

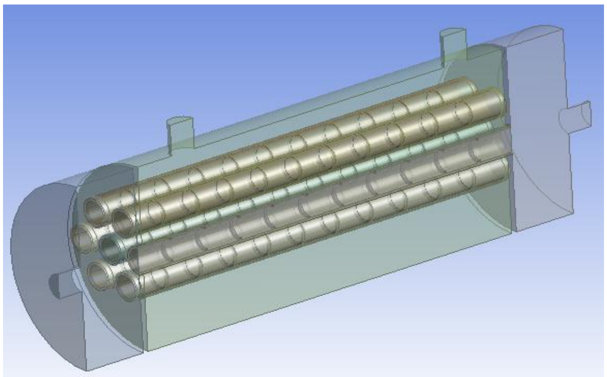

Fig.2Fluid model assembly of circular fin tube EGR cooler

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.

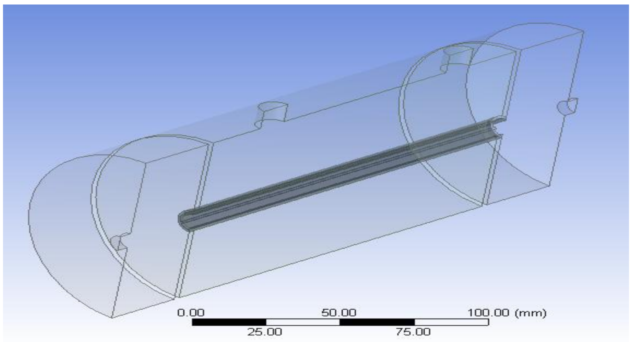

Fig.3Fluid model assembly of rectangular fin tube EGR cooler

Fig -3 shows the fluid volume which will be occupied by hot gases and cooling water when they are inside EGR cooler. In this model circular fins are replaced by rectangular fins to find out the change in the exhaust temperature of EGR cooler and effectiveness of the cooler.

VI. RESULTS AND DISCUSSION

CFD results for different type of EGR cooler

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

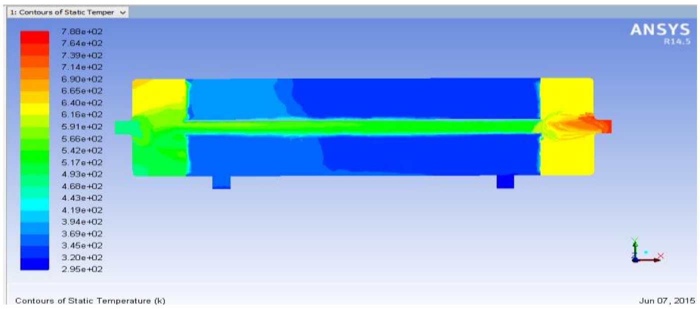

Fig. 4 temperature contour of plain tube EGR cooler

Above figure shows the temperature contour of plain tube EGR cooler. This contour shows the variation of temperature along the tube length red color shows the inlet temperature of the hot exhaust gases as they move forward heat is extracted by the coolant water and temperature of gases reduced and the temperature of the coolant is increased because it takes heat from exhaust gases. Green and yellow color shows the outlet temperature of exhaust gases this temperature can be read out by the temperature scale. Blue color shows the temperature of coolant. As we are not able to differentiate the temperature change of coolant in the temperature contour because change in temperature occurs only in blue zone of temperature contour.

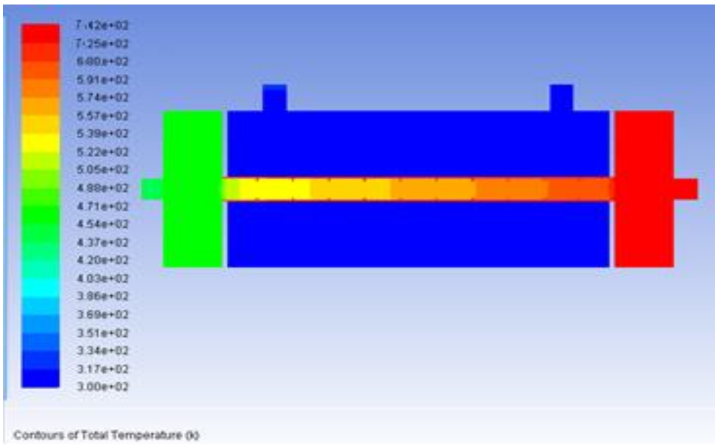

Fig. 5 temperature contour of circular fin tube EGR cooler

Above figure shows the temperature contour of circular fin tube EGR cooler. In this contour hot exhaust enter about 739K temperature inside the tube and as they move ahead the temperature of gases decreased and out let of the tube temperature is obtain about 547K this temperature can be read out by the temperature scale of the contour. Temperature drop in the circular fin tube is more compared to plain tube EGR cooler because surface area for heat transfer between cold fluid and hot fluid has been increased. Similarly temperature drop for the coolant is taking place in blue zone of the scale. It means rise in the temperature of the coolant is varying between 30K.

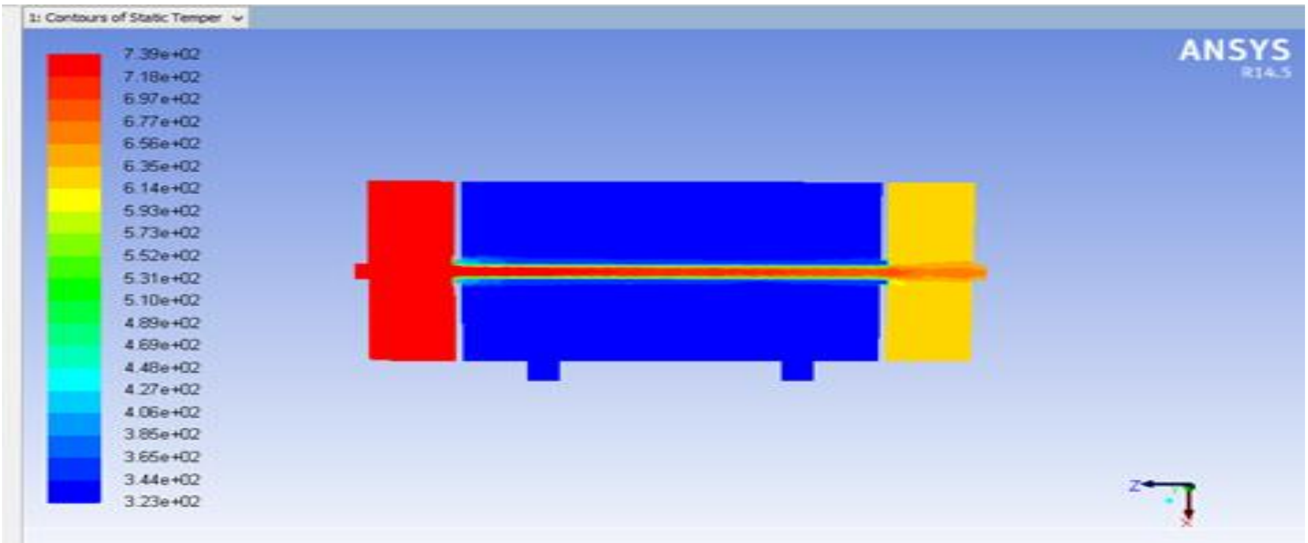

Fig. 6 temperature contour of rectangular fin tube EGR cooler

Above figure shows the temperature contour of rectangular finned EGR cooler. This contour shows the variation of temperature along the tube length red color shows the inlet temperature of exhaust gases as gases move forward heat is extracted by the coolant water and temperature of gases reduced and the temperature of the coolant is increased because it takes heat from exhaust gases. In the rectangular fin tube temperature drop of hot exhaust gases is more as compared to circular fin tube because root base area of fins is more in rectangular fin tube.

Parameter	**Model-a**		**Model-b**		**Model-c**	
	Inlet Section	**Outlet Section**	**Inlet Section**	**Outlet Section**	**Inlet Section**	**Outlet Section**

Mean Temp. of exhaust gas (K)	739.0	615.7	739.0	595.5	739	590.8
Effectiveness (ε)	30.3%		34.6%		35.1%	

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

In the above table CFD results have been shown for different type of EGR coolers. In above table Model-a means plain tube, model-b means circular fin tube and model-c means rectangular fin tube. Table shows the outlet temperature and effectiveness of different type of EGR cooler when CFD analysis is performed by taking a single tube of every type of EGR cooler model.

Parameter	**Plain tube**	**Circular fin tube**	**Rectangular fin tube**
Outlet Exhaust temp.	481.3	458.2	431.5
Effectiveness(ε)	61.2%	67.3%	73.5%

Table 4: Analytical results of different type of fin tube

Above table shows the analytical results of different type of EGR cooler. In above table it is clear that temperature drop for circular fin tube is more compared to plain tube EGR cooler and hence effectiveness of circular fin tube EGR cooler is more compared to plain tube EGR cooler. Temperature drop for rectangular fin tube EGR cooler is more compared to circular fin tube EGR cooler. So effectiveness of rectangular fin tube EGR cooler is more effective compared to circular fin tube EGR cooler.

VII. COMPARISON OF CFD RESULTS AND ANALYTICAL RESULTS FOR DIFFERENT TYPE OF EGR COOLER

	Analytical results(For whole system)			CFD results(For single tube)			% Error		
Parameter	Model a	Model b	Model c	Model a	Model b	Model c	A	B	C
Temperature	481.3K	458.37K	431.7K	615.5K	595.1K	590.87K	27.8%	29.9%	36.1%
Effectiveness	61.2%	67.3%	73.35%	30.3%	34.6%	35.1%	30.9%	32.1%	38%

Table5: Comparative analysis of results

VIII. VARIATION OF RESULTS BETWEEN CFD AND ANALYTICAL

1. During CFD results calculation I took coarse meshing of system because of this number of nodes and elements reduced and I got approximate value of temperature change. If I choose fine meshing of system my results would be more accurate. Selection of meshing method affects our results seriously.

2. During CFD analysis, I have not taken whole system for performing CFD analysis, just took a single tube, by performing CFD analysis on this single tube, temperature and velocity contour obtained for a single tube not for the whole EGR cooler. Compare to whole system (EGR cooler) number of nodes and elements would be less in a single tube because of this approximate value of temperature change of exhaust gases obtained.

Reason for performing CFD analysis on single tube of each type of EGR cooler is that in our institution ANASYS lab is under developing phase. For performing CFD analysis on heat exchanger (EGR cooler) well equipped lab and system is a basic need because during mesh generation in EGR cooler number of nodes and elements are generated in lakhs.

IX. CONCLUSION

An approach was carried out for predicting the performance of EGR cooler with fins and without fins by using CFD technique. These CFD results are compared with analytical results.

Here an approach has been taken to make comparative study of heat transfer and temperature drop between plain tube, circular fin tube and rectangular fin tube. Results show that in each case different temperature and heat transfer occurred.

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 have less surface area than finned tubes. In case of circular fins heat transfer is increased by 8.36% compared to plain tube and in case of rectangular fin heat transfer is increased by 63% as compared to plain tube. Hence effectiveness of the EGR cooler in both cases is increased.

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.

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