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Theoretical Design of Exhaust Gas Recirculation System in Compression Ignition Engine

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Abstract—*Air pollution is major problem faced on road as well as off road applications. These pollution causes hazardous effects on human health as well as environment. Exhaust Gas Recirculation is very effective technique to reduce emission from diesel engine. In the present work design and development of EGR system is done for Single cylinder, four strokes compression engine. Shell and tube heat exchanger of EGR system is designed for cooling hot gasses and increasing volumetric efficiency. Design of shell and tube EGR cooler is done with theoretical calculation. Cold EGR system is useful for effective working of exhaust gas recirculation system. The obtained results are purely based on the theoretical calculations by changing the number of tubes and diameter of tube of shell and tube EGR cooler. The best design of EGR cooler is based on its effectiveness, overall heat transfer rate and manufacturing cost. At the successful completion of present work it is expected that designed and developed EGR system will work efficiently to reduce NOx significantly.*

1. INTRODUCTION

The Theory of compressed-ignition (CI) Engines is developed by Rudolf Diesel. The use of automobiles, moving machinery and off road vehicle have created some serious issues. Due to this in recent past years strong emission legislation are imposed on NOx, particulate matter and smoke emitted from diesel engine.

Exhaust gas recirculation technique works with a principle of reducing the oxygen content from fresh air and combustion flame temperature. At higher temperature (at about 2000k) and higher molecules of oxygen an oxides of nitrogen(NOx) formation takes place [1]. EGR is reduce nitrogen oxides (NOx) by decreasing flame temperature and the oxygen concentration of the working fluid in the combustion chamber. Exhaust gas recirculation technique is more effective when the hot exhaust gas is cooled before it enters in the combustion chamber. This done by using EGR cooler.[8].Cold EGR having more advantages over the hot EGR and cold EGR reduces more percentage of NOx as compared to hot EGR[9].

2. EXHAUST GAS RECIRCULATION SYSTEM WITH EGR COOLER

In the present work the engine selected for Exhaust gas recirculation system is Kirloskar, four-stroke, single-cylinder, water-cooled, naturally aspirated, DI (open chamber), diesel engine. Figure.1 shows photograph of set-up before engine modifications.

Fig. 1: Overall view of engine

The block diagram of modified engine with EGR is shown in Fig. 2. The EGR system is fabricated as per requirements and will be used in the set-up. A short loop cooled EGR system is chosen for study. To gain significant EGR effects, several components like EGR cooler, EGR valve etc. are incorporated in design shown in Fig. 2.

Two valves are used to control EGR rate: one before EGR cooler and second at outlet of EGR cooler. Further, the EGR pipe line is connected to air intake system by means of T connection and the integrated system is connected to intake manifold.

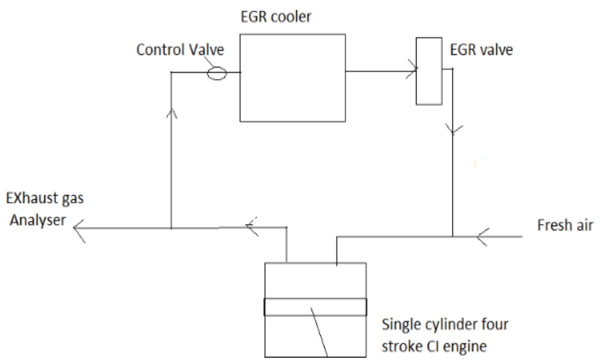


Fig. 2: Exhaust gas recirculation system

3. PARAMETRIC STUDY

The effect of changing different design parameter is studied under parametric study.

3.1. Design requirement of an EGR system consist of various a aspects as listed below

1. Exhaust gas parameters.
2. Coolant parameter.
3. EGR cooler design.
4. Gas route pipes.
5. EGR valve and its placement.

3.1.1. Exhaust Gas Parameters

The Exhaust gas before entering and leaving the EGR cooler is need to be measured. Parameters are Rate of gas flow, Inlet gas temperature (before the EGR cooler),Outlet gas temperature(after the EGR cooler), Working pressure.

3.1.2. Coolant Parameters

In EGR cooler hot fluid is hot gasses and cold fluid is water. Water side parameter before entering and leaving the EGR cooler are need to be measured. parameters are Rate of water flow, Inlet water temperature, Outlet water temperature.

3.1.3. EGR Cooler Design

"EGR cooler is the equipment which transfer the energy from hot fluid to cold fluid". EGR cooler is installed to cool the EGR gases before mixing with the fresh air charge which reduces NOx formation. Step by step approach of EGR Cooler design process are given bellow.

i) Identify application
ii) Selection of heat exchanger
iii) Evaluate logarithmic mean temperature difference (LMTD)
iv) Decide dimension
v) Baffle design

i) Identify application

Identify the required thermodynamics properties(e.g. Temperature, specific heat, mass flow rate) of hot and cold fluid, perform energy balance and calculate heat transfer rate.

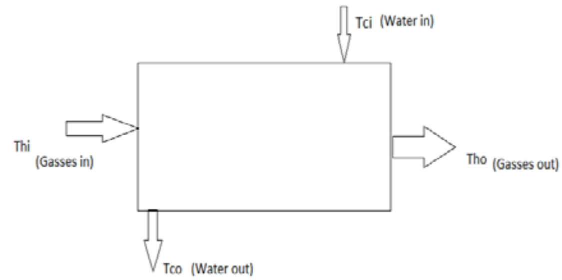


Fig. 3: Simple representation of EGR cooler

Here,
Thi = Inlet temperature of gasses - 525 ^{o}C
Tho = Outlet temperature of gasses - 130 ^{o}C
Tci = Inlet Temperature of water - 25 ^{o}C
Tco = Outlet Temperature of water - 70 ^{o}C
Cph = Specific heat of hot Gasses - 1050 J/Kg.K
Cpc = Specific heat of cold fluid - 4185 J/Kg.K

Mass flow rate of exhaust gasses and water

Me = Ma + Mf **[6]**
Where, Me = Mass flow rate of Exhaust gas (Kg/sec).
Ma = Mass flow rate of air (Kg/sec).
Mf = Mass flow rate of fuel injected into the cylinder (Kg/sec).
∴ Me = 24.8 + 1.34
= 25.42 Kg/hr.
Me = 7.06 X 10^{-3} Kg/sec.
Perform Energy balance,
MhX CphX (Thi - Tho) = Mc X Cpc X (Tci - Tco)
7.06 X 10^{-3} X 1050 X (525-125) = Mc X 4185 X (70 - 25).
∴ **Mc = 15.55 X 10^{-3} Kg/sec.**

Heat flow rate Q = Mass flow rate **X** Specific heat **X** temperature difference
∴ Q = Mh X Cph X (Thi - Tho) OR
Q = Mc X Cpc X (Tci - Tco)
∴ Q = 7.06 X 10^{-3} X 1050 X (525-125)
∴ Q = 2928.135 J/s
∴ **Heat transfer rate = 2928.135 J/s**

ii) Selection of heat exchanger

The heat exchanger in operation must withstand the stresses produced by the operating pressure and the temperature differences between two fluids. The most versatile heat exchangers for a broad range of operating pressures and temperatures are shell-and-tube exchangers[7]. Shell and tube type heat exchanger is selected which fulfil our requirement. Shell and tube heat exchanger is shown in Fig. 4.

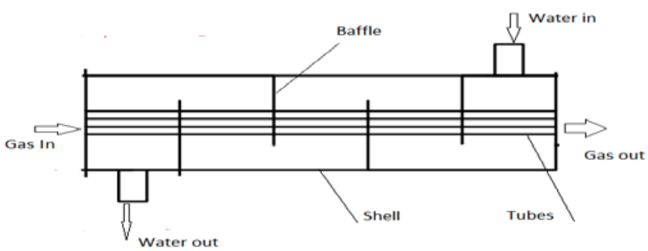


Fig. 4: Shell and tube EGR cooler.

The major components of a shell-and-tube exchanger are tubes, baffles and shell. Depending on the applications, a specific combination of geometrical variables or types associated with each component is selected. Counter flow shell and tube EGR cooler is used in design, because it minimises the thermal stresses, having uniform heat transfer rate [2].

(iii) Evaluate logarithmic mean temperature difference (LMTD)

The larger the LMTD, the more heat is transferred.

$\Delta T1 = 525 - 70 = 455\ ^oC$

$\Delta T2 = 130 - 25 = 105\ ^oC$

$LMTD = \frac{\Delta T1 - \Delta T2}{\ln(\Delta T1 / \Delta T2)}$

$\therefore LMTD = \frac{455 - 105}{\ln(455/105)}$

$\therefore$ **LMTD = 238 ^{o}C or ^{o}K.**

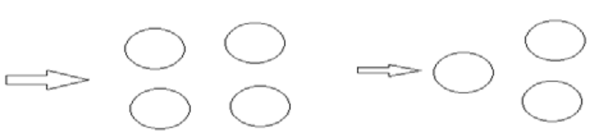
iv) Decide dimension

a) Tube arrangement

There are two types of tube arrangement, Aligned and Staggered as shown in Fig. 5.

Triangular pattern is complicated tube sheet construction.

Square pattern simplifies cleaning and has a lower shell side pressure drop[10].



(a) (b)

Fig. 5. (a) Aligned tube arrangement (b) Staggered tube arrangement

Tube pitch is the shortest centre to centre distance between the adjacent tubes (see Fig. 6).

PT = D + C

PT = tube pitch, D = tube diameter, C = clearance

The geometry of tube bank is depend upon, tube diameter D, longitudinal pitch S_L, transverse Pitch S_T.

b) Outside heat transfer coefficient -

The heat transfer coefficient associated with a tube is determined by its position in the bank. The tubes of the first few rows act as a turbulence-generating grid, which increases the heat transfer coefficient for tubes in the following rows. Flow direction over tube is shown in Fig. 6.

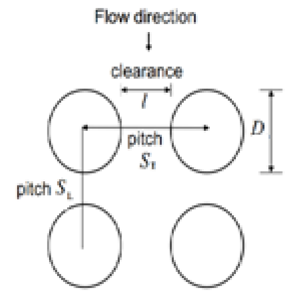


Fig. 6: Flow direction over tube

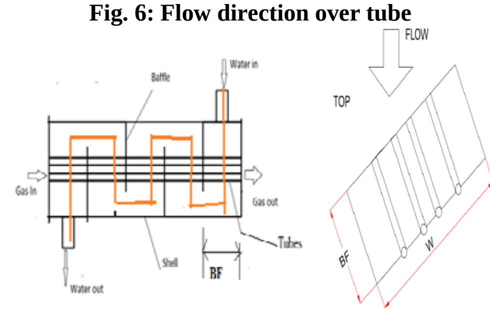


Fig. 7: Side view of EGR cooler

Outside heat transfer coefficient ho [2] $= \frac{Nu.k}{D}$

Nu [3] = C_1 **X** C_2 **X** 1.13 **X** R^m **X** $Pr^{1/3}$

Nu - Nussetl number

R- Reynolds number

Pr -Prandtl number

R [2] $= \frac{\rho\, V_{max}\, D}{\mu}$

D - Diameter of tube

μ - Viscosity of water

ρ - Density of water

This equation of Nu is valid for number of rows of tube is less than 10 i.e. (N_L <10).

C_2, C_1 and m is obtain from table7.5**[3]**. The Reynolds number R is based on Vmax the maximum fluid velocity occurring within the tube bank.[3]

For the aligned arrangement, from continuity, (see Fig. 6).

$V_\infty . S_T = V_{max} .(S_T - D)$

$\therefore V_{max} = \frac{ST\, V\infty}{(ST - D)}$

But, Flow velocity approaching tube $V_\infty = \frac{Mc}{\rho\, a}$

In Fig. 7. Flow area (a) = BF **X** W

BF - Length of tube within the baffle

W - Width of EGR cooler

W = S_T (N + 2)

N - Number of tube per row, 4 tubes per row chosen.

S_T - Transvers pitch = 25 mm

$\therefore$ W = 25 (4+2)

$\therefore$ **W = 150mm**

Choose BF = (2/3) W
∴ BF = (2/3) 150
∴ **BF = 100mm**
∴ Flow area (a) = 0.1 X 0.15
∴ **Flow area = 0.015 m^2**
∴ $V_\infty = \frac{15.55 \text{ X } 10^{-3}}{1000 \text{ X } 0.015}$
∴ **V_∞ = 1.0366 X 10^{-3} m/s**
∴ $V_{max} = \frac{ST\ V\infty}{(ST - D)}$
∴ $V_{max} = \frac{25 \text{ X } 1.0366 \text{ X } 10-3}{(25 - D)}$

The suitable diameter and number of tube can be taken from table 1.in order to get the best design of EGR cooler i.e. Effectiveness is high, compact size, less manufacturing cast etc. Theoretical calculations are performed using the design formulae. The parameters are varied to get the optimum design of the heat exchanger for EGR system.

Table 1

Sr. No	Diameter(mm) of tube	Number of tube
1	8	4, 8, 12, 16, 20
2	12	4, 8, 12, 16, 20
3	16	4, 8, 12, 16, 20
4	20	4, 8, 12, 16, 20

Case 1. In this case changing the number of tube and keeping the diameter of tube constant(**8 mm**).
D = 8mm
W = 150mm
BF = 100mm
Flow area = 0.015 m^2
V_∞ = 1.0366 X 10^{-3} m/s
∴ $V_{max} = \frac{ST\ V\infty}{(ST - D)}$ ∴ Vmax = $\frac{25 \text{ X} 1.0366 \text{ X } 10-3}{(25 - 8)}$
∴ **Vmax = 1.5244X 10^{-3} m/s.**

$R = \frac{\rho\ Vmax\ \ D}{\mu} = \frac{10^3 \text{ X } 1.52244 \text{ X } 10^{-3} \text{ X } 8 \text{ X } 10^{-3}}{577 \text{X} 10^{-6}}$
R = 21.135

Nu = C_1 **X** C_2 **X** 1.13 **X** R^m **X** $Pr^{1/3}$
Mean temperature = $\frac{70+25}{2}$ = 47.5 ^oC = 320.5 ^oK
At 320.5 ^oK
μ = 577 X 10^{-6} Ns/m^2
k = 640 X 10^{-3}W/mK
Pr = 3.77

Calculation of C_1, C_2 and m
S_T/D = 25/8 = 3.12
S_L/D = 25/8 = 3.12
From **table7.5[3]** , C_1 = 0.286 , m = 0.608
From table, Value of C_2 changes when number of rows changes
For 4 tube, number of row of tube = 1
∴ C_2 = 0.64
For 8 tube, number of rows of tube = 2
∴ C_2 = 0.80
For 12 tube ,number of rows of tube = 3
∴ C_2 = 0.87
For 16 tube, number of rows of tube = 4
∴ C_2 = 0.90
For 15 tube, number of rows of tube = 5
∴ C_2 = 0.92
∴ as C_2 changes values of Nu changes

Table 2: Nu values for various number of tube

Nu for 4 tubes	2.0575
Nu for 8 tubes	2.572
Nu for 12 tubes	2.7971
Nu for 16 tubes	2.893
Nu for 20 tubes	2.9578

Outside heat transfer coefficient ho = $\frac{Nu.k}{D}$
ho = $\frac{Nu \text{ X } 640 \text{ X } 10-3.}{8 \text{ X } 10-3}$

Table 3: Ho values for various number of tube

ho for 4 tubes	164.6
ho for 8 tubes	205.76
ho for 12 tubes	223.768
ho for 16 tubes	231.48
ho for 20 tubes	236.62

C)Heat transfer coefficient inside the tube.
hi = $\frac{Nu.k}{D}$
R = $\frac{4\ Me}{\Pi D\ \mu N}$
Nu[3] = 0.023 **X** $R^{4/5}$ **X** $Pr^{1/3}$
Viscosity of gas (μ) = 30.6 X 10^{-6} Ns/m^2.
R = $\frac{4\ Me}{\Pi D\ \mu N}$
∴ R = $\frac{4 \text{ X } 7.06 \text{ X } 10^{-3}}{\Pi \text{X } 8 \text{ X } 10^{-3} \text{X} 30.6 \text{ X} 10^{-6} \text{ X N}}$

∴ R = $\frac{36720.062}{N}$

Table 4: R values for various number of tube

R for 4 tubes	9180.0155
R for 8 tubes	4590.008
R for 12 tubes	3060.005
R for 16 tubes	2295.004
R for 20 tubes	1836.0031

Nu - Nussetl number
Nu = 0.02032 X $R^{4/5}$

Table 5: Nu values for various number of tube

Nu for 4 tubes	30.074
Nu for 8 tubes	17.2726
Nu for 12 tubes	12.488
Nu for 16 tubes	9.921
Nu for 20 tubes	8.298

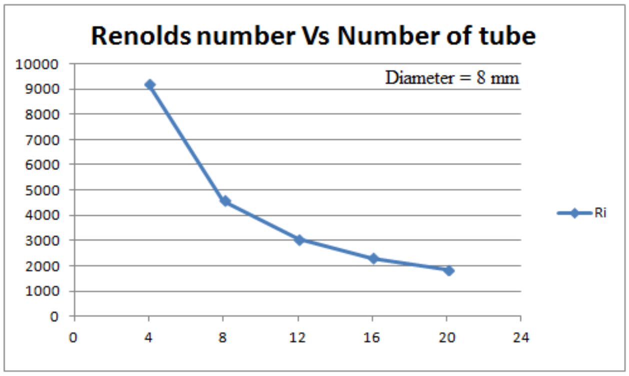


Fig. 9: Relation between Reynolds number Vs Number of tubes.

∴ Heat transfer coefficient inside the tube.

$hi^{[11]} = \frac{Nu.k}{D}$

$hi = \frac{Nu.X\ 0.0466}{8\ X\ 10^{-3}}$

Table 6: Hi values for various number of tube

hi for 4 tubes	175.181
hi for 8 tubes	100.81
hi for 12 tubes	72.743
hi for 16 tubes	57.743
hi for 20 tubes	48.34

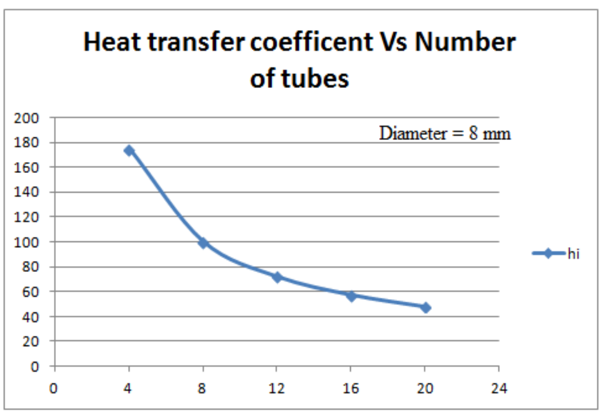


Fig. 10: Relation between Heat transfer coefficient Vs Number of tubes

Overall heat transfer coefficient

$\frac{1}{U} = \frac{1}{ho} + \frac{1}{hi}$

Table 7: U values for various number of tube

U for 4 tubes	84.86
U for 8 tubes	67.57
U for 12 tubes	54.897
U for 16 tubes	46.295
U for 20 tubes	40.139

Heat flow rate Q = U. A. LMTD

∴ Q = U . ΠDNL. LMTD

$\therefore L = \frac{Q}{U\ \Pi DN\ LMTD.} = \frac{2928.135}{UN\ X\ \Pi X\ 8\ X\ 10^{-3} X\ 238}$

$\therefore L = \frac{489.52}{UN}$

∴ Length of tube in m

Table 8: L values for various number of tube

L for 4 tubes	1.442
L for 8 tubes	0.9056
L for 12 tubes	0.7431
L for 16 tubes	0.66158
L for 20 tubes	0.61

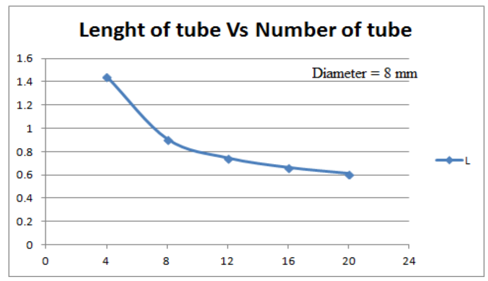


Fig. 11: Relation between length of tube Vs number of tube

Case1 are put in tabular form (in table.9), similarly for tube diameter 12mm, 16mm, 20mm the various parameter are calculated and represented in table no. 10 to 12.

V) Baffles Design-

Baffles are integral part of the shell and tube heat exchanger design. The function of baffle is to support the tube bundles and to prevent effects of vibration from the flow [7]**.** A baffle cut ranges from 20 to 25% provide a good heat-transfer with the reasonable pressure drop. The % cut for segmental baffle refers to the cut away height from its diameter.

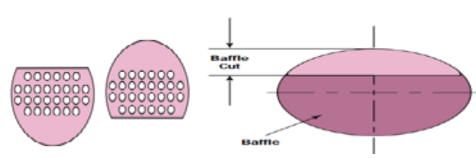


Fig. 12: Geometry of baffle[7]

3.1.4. Gas routes pipes

Pipes carry exhaust hot gasses from exhaust manifold to inlet manifold, it should withstand with high temperature about 700^0C and pressure about 3 bar. also pipes should be compact and generally small route.

3.1.5. EGR valve and its placement.

EGR valve is most important part of the exhaust gas recirculation system. The recirculated exhaust gas flow controlled by EGR valve. Bypass for the exhaust gas is provided along with the manually controlled EGR valve to measure and control the quantity of exhaust gas.

EGR rate based on mass flow rate.

$$\%EGR = \frac{m_{EGR}}{m_{total\ \ suction}} \text{ X } 100$$

However, mass of re-circulated exhaust gas can be calculated based on difference in manometer column for consecutive revolution (position) of EGR valve. The EGR rate will estimated as for every half revolution of valve. EGR valve can placed before or after EGR cooler. If valve is placed before the cooler then hot gasses directly flows through the valve due to which it undergoes to high temperature on other hand if EGR valve is placed after EGR cooler then it sustained to gasses having less temperature. Hence Life of EGR valve is more when it is placed after EGR cooler.

4. CONCLUSION

Using Exhaust gas recirculation system emission can be effectively reduced. As EGR cooler is decreases exhaust gas temperature, cold EGR system is more effective than hot EGR system. The results are purely based on the theoretical calculation. The various combination of tube diameter and number of tube are tested. The best design criteria of EGR cooler are overall heat transfer coefficient must be in range of 20-30W/m^{2}k, high effectiveness, less manufacturing cost. This is possible when we select pair, 8mm diameter and 20 number of tube(table 9). With this combination we can design best EGR cooler to reduce emission from the diesel engine effectively.

Table 9: Tube diameter = 8 mm

Diameter	**Number of tube**	**Ho**	**Hi**	**U**	**L**	**Effectiveness**	**Preference**
8	4	164.6	175.181	84.86	1.442	0.79086	-
8	8	205.76	100.61	67.57	0.9056	0.79062	-
8	12	223.768	72.473	54.897	0.7431	0.790924	3
8	16	231.48	57.79	46.245	0.65158	0.790913	2
8	20	236.62	48.34	40.139	0.61	0.791026	1

Table 10: Tube diameter = 12 mm

Diameter	**Number of tube**	**Ho**	**Hi**	**U**	**L**	**Effectiveness**	**Preference**
12	4	179.2	80.8	55.854	1.4607	0.7821	-
12	8	180.912	48.49	38.24	1.06676	0.789	-
12	12	196.74	35.058	29.36	0.9146	0.785	-
12	16	203.528	27.85	24.135	0.831	0.788955	5
12	20	208.05	23.3	20.8	0.7901	0.793118	4

Table 11: Tube diameter = 16 mm

Diameter	**Number of tube**	**Ho**	**Hi**	**U**	**L**	**Effectiveness**	**Preference**
16	4	170.176	50.307	38.829	1.5759	0.79091	-
16	8	212.72	28.8949	25.44	1.2026	0.7909	-
16	12	231.332	20.8914	19.161	1.064	0.7906	-
16	16	239.312	16.596	15.52	0.9856	0.79079	-
16	20	244.64	13.882	13.136	0.9316	0.7908	-

Table 12: Tube diameter = 20 mm

Diameter	Number of tube	ho	Hi	U	L	Effectiveness	Preference
20	4	270.848	32.2235	28.79	1.70032	0.7909	-
20	8	338.56	18.5061	17.54	1.395	0.79072	-
20	12	368.16	13.38	12.91	1.239	0.78452	-
20	16	380.896	10.63	10.34	1.1835	0.78819	-
20	20	389.344	8.89	8.69	1.1266	0.7907	-

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