A Review Study on Exhaust Gas Recirculation (EGR) Cooler Design and Using CFD to Enhance Its Performance

Ibrahim Hussain Shah[1] Bhupendra Singh[2]
[1]Assistant Professor [2] PG Scholar
[1,2]Department of Mechanical Engineering
[1,2]Institute of Engineering and Technology, Devi Ahilya Vishwavidyalaya, Indore

Abstract— Strict emission standards are now in place that set specific limits to the amount that can be released into the environment. Reduction of exhaust emission of a vehicle is done through an EGR technique. EGR coolers are subjected to severe fouling such that their thermal efficiency can drop as much as 30 percent within a very short period of time. Durability of EGR cooler performance is key issue that affects the function of EGR system as anti-pollutant device. Decrease of thermal efficiency and increase of gas pressure drop caused by soot deposition implies higher EGR gas temperature and lower EGR flow. Selection of heat exchanger technology and definition of design parameters have an important effect on this degradation. This paper reviews a compendium of different tests, where different technologies and sizes of EGR cooler have been exposed to different engine test cycles. The focus is going to be mainly on Computation fluid dynamics (CFD) and to increase effectiveness of EGR cooler used in EGR system.

Key words: EGR cooler, effectiveness, Computation Fluid Dynamics

I. INTRODUCTION

Exhaust gas recirculation (EGR) has been developed to achieve the lowest possible engine out emissions. EGR is capable of achieving up to 50 percent reduction in NOx emissions (6). Exhaust gas recirculation (EGR) is used to dilute intake air with some fraction of exhaust gas to the combustion temperatures resulting in lower engine-out NOx emissions (6). This process is mostly done by using a heat exchanger (mostly shell and tube heat exchanger), exhaust gas flowing inside the tube and coolant in the shell (10). For reducing vehicular emissions, baseline technologies are being used which include direct injection, turbo-charging, air-to-air inter-cooling, combustion optimization with and without swirl support, multi-valve cylinder head, advanced high pressure injection system i.e. split injection or rate shaping, electronic management system, lube oil consumption control etc (1). Diesel engines are typically characterized by low fuel consumption and very low CO2 emissions (11). The limits imposed by the new emission legislation, such as EURO4, EURO5, EPA07, and EPA10, demand a high exhaust gas cooler performance. Thus, by year 2008 the EGR cooler for EURO5 vehicle must meet emission limits of 2.0 g/kWh of NOx and 0.025 g/kWh of PM and also proposed norms of EURO6(2013) NOx .04g/kWh and PM .01g/kWh (11). So, technologies like exhaust gas recirculation (EGR), soot traps and exhaust gas after-treatment are essential to cater to the challenges posed by increasingly stringent environmental emission legislations. 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. (8)

A. Mechanism of formation of pollutant

1) Mechanism of formation of Carbon Monoxide (CO)

CO is generally formed when the mixture is rich in fuel. The amount of CO formation increases as the mixture becomes more and richer in fuel. A small amount of CO will come out of the exhaust even when the mixture is slightly lean in fuel because air- fuel mixture is not homogenous and equilibrium is not established when the products pass to the exhaust. At the high temperature developed during the combustion, the products formed are unstable and following reactions take place before the equilibrium is established (12)**.**

$$2C+O_2 = 2CO$$

As the products cool down to exhaust temperature, major part of CO reacts with oxygen to form CO2. However, a relatively small amount of CO will remain in exhaust (12).

1) Mechanism of formation of Hydrocarbons (HC)

Hydrocarbons, derived from unburnt fuel emitted by exhausts, engine crankcase fumes and vapor escaping from the carburetor are also harmful to health. Hydrocarbons appears in exhaust gas due to local rich mixture pockets at much lower temperature than the combustion chamber and due to flame quenching near the metallic walls. A significant amount of this unburnt HC may burn during expansion and exhaust strokes if oxygen concentration and exhaust temperature is suitable for complete oxidation (12).

2) Mechanism of formation of nitric oxide (NO)

Oxides of nitrogen is produced in very small quantities can cause pollution. While prolonged exposure of oxides of nitrogen is dangerous to health. Oxides of nitrogen which occurs only in the engine exhaust are a combination of nitric oxide (NO) and nitrogen dioxide (NO2). Nitrogen and oxygen react at relatively high temperature. NO is formed inside the combustion chamber in post-flame combustion process in the high temperature region. The high peak combustion temperature and availability of oxygen are the main reasons for the formation of NOx. In the present of oxygen inside the combustion chamber at high combustion temperatures the following chemical reactions will takes place behind the flame (12). Zoldowich mechanism for formation of nitric oxide.

$$N_2+O = NO + N$$

$$N + O_2 = NO + O$$
$$N_2 + OH = NO + N$$

Mechanism of formation of particulate matters The diesel engine combustion begins around 5◦ after start of injection (ASI) in a locally rich premixed zone as described in and depicted reaction . The products from this early reaction are small, partially burnt fragments of hydrocarbons which are generally believed to lead to the formation of polycyclic aromatic hydrocarbons (PAH) that constitute the building blocks for particulates in flames [5]. When the air entrained during the premixed burn is entirely consumed, the temperature reached by this partial oxidation is about 1600 K and the reaction products (CO, CO_2, fuel fragments and water vapour) will subsequently receive heat from the hot diffusion flame to form an environment favorable for the formation and agglomeration of soot particles. The fuel fragments and soot particles are subsequently transported through the interior of the plume toward the boundary of the diffusion flame sheath where they are oxidized in a thin reaction layer at temperatures around 2,700 K. Experiments show that these particulates are completely consumed by the hot diffusion flame sheath so that diesel soot emissions appear to be the result of quenching this final phase of oxidation (13).

B. Control of oxides of nitrogen (NOX)

Many theoretical and experimental investigation shows that the concentration of NOx in the exhaust gas is closely related to the peak cycle temperature and available amount of oxygen in the combustion chamber. Any process to reduce cylinder peak temperature and concentration of oxygen will reduce the oxides of nitrogen. This suggests a number of methods for reducing the level of nitrogen oxides. Among these the dilution of fuel-air mixture entering the engine cylinder with an inert or non-combustible substance is one which absorbs a portion energy released during the combustion, thereby affecting an overall reduction in the combustion temperature and consequently in the NOx emission level. The following are the three methods for reducing peak cycle temperature and thereby reducing NOx emission (12) .

(1) Water injection.
(2) Catalyst
(3) Exhaust gas recirculation (EGR)

1) Water injection

Nitrogen oxides NOx reduction is a function of water injection rate. NOx emission reduces with increase in water injection rate per kg of fuel. The specific fuel consumption decreases a few percent at medium water injection rate. The water injection system is used as a device for controlling the NOx emission from the engine exhaust (12).

2) Catalyst

A copper catalyst has been used to reduce the NOx emission from engine in the presence of CO. Catalytic converter package is use to control the emission levels of various pollutants by changing the chemical characteristics of the exhaust gases. Catalyst materials such as platinum and palladium are applied to a ceramic support which has been treated with an aluminium oxide wash coat. This results in as extremely porous structure providing a large surface area to stimulate the combination of oxygen with HC and CO. This oxidation process converts most of these compounds to water vapour and carbon-dioxide (12).

3) Exhaust gas recirculation

EGR is commonly used to reduce NOx in S.I. engines as well as C.I. engines. Fig (1) shows the arrangement of exhaust gas recirculation (EGR) system. The principle of EGR is to recirculate about 10% to 30% of the exhaust gases back into the inlet manifold where it mixes with the fresh air and this will reduces the quantity of O_2 available for combustion (1,12). This reduces the O_2 concentration and dilutes the intake charge, and reduces the peak combustion temperature inside the combustion chamber which will simultaneously reduce the NOx formation. About 15% recycle of exhaust gas will reduce NOx emission by about 80%. It should be noted that most of the NOx emission occurs during lean mixture limits when exhaust gas recirculation is least effective. The exhaust gas which is sent into the combustion chamber has to be cooled so that the volumetric efficiency of the engine can be increased.

From above three methods, EGR is the most efficient and widely used system to control the formation of oxides of nitrogen inside the combustion chamber of I.C. engine. The exhaust gas for recirculation is taken through an orifice and passed through control valves for regulation of the quantity of recirculation. Normally exhaust gas recirculation is shut off during idle to prevent rough engine operation (12).

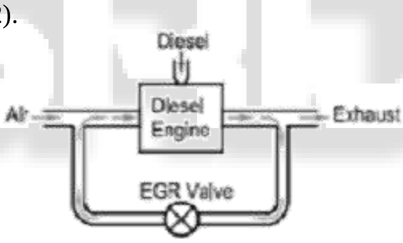


Fig. 1. Exhaust Gas Recirculation

C. Reduction technologies of particulate matters

1) Particulate Filters

Diesel Particulate Filters (DPF) have been considered as a solution to the PM problem for twenty years. Although not really necessary in Europe to satisfy Euro IV, much effort is being done on developing filters in Europe, lead by Peugeot's introduction of a DPF in serial production in

$$\%\,EGR = \frac{\text{Mass of air admitted without EGR} - \text{Mass of air admitted with EGR}}{\text{Mass of air admitted without EGR}}$$

2001. A typical filter is the ceramic wall-flow filter, where the exhaust gas is forced to flow through the walls of the monolith which removes PM very efficiently. To avoid clogging up of the filter, the PM has to be oxidized, either periodically or continuously. Direct oxidation by O_2 is accomplished at temperatures of around 550◦C, where the carbonaceous soot oxidizes. However, the exhaust temperature of the diesel engines under normal operation is in the range of 150◦C to 200◦C, therefore, efforts are being made to reduce the balance point temperature (BPT) (13).

Filters are most effective at removing solid accumulation mode particles (letting through mainly SOF and sulphates which are almost completely gaseous at typical filter temperatures), while catalysts remove mainly organic compounds that will contribute to SOF and nuclei mode. However, numerous studies have demonstrated that filters take out more than 90% nanoparticles, but it might be that gaseous nanoparticle precursors are not removed and sulphate nanoparticles might actually increase[13]. DPFs are very effective (up to 95% removal of PM by mass) if the pore opening is less than 40 to 80 µm. Durability of properly operated filter systems has been shown to be exceptional over as much as 600,000 km. It is shown that increasing the filter diameter/length ratio for any given filter volume will reduce pressure drop and also decrease peak temperatures in the filter during uncontrolled regeneration (13).

2) Regeneration Strategies

As mentioned above, reducing the balance point temperature is a crucial factor to enable regeneration at lower temperatures. This can be done by reducing the sulphur content, coating a catalyst such as platinum onto the wall-flow filter, introducing an oxidation catalyst before the filter (so-called CRT in which the catalyst oxidizes NOx to NO2 which is a strong oxidizing agent for soot at 250◦C, but at the same time, it forms sulphate particulates (23)), using non-thermal plasma to replace the oxidation catalyst (the plasma converts NO to NO2 without significant conversion of SO2), or using fuel-borne catalysts (e. g. iron or cerium additives which strengthen radical-carbon bonds which play an important role in soot oxidation) (12). So far, the diesel exhaust temperatures can be too low to regenerate the filters under all driving conditions; hence, active regeneration techniques are still needed (13).

D. *Classification of EGR systems*

Various EGR systems have been classified on the basis of EGR temperature, configuration and pressure.

Classification based on temperature (1)

(1) Hot EGR: Exhaust gas is recirculated without being cooled, resulting in increased intake Charge temperature.
(2) Fully cooled EGR: Exhaust gas is fully cooled before mixing with fresh in take air using a water-cooled heat exchanger. In this case, the moisture present in the exhaust gas may condense and the resulting water droplets may cause undesirable effects inside the engine cylinder.
(3) (iii) Partly cooled EGR: To avoid water condensation, the temperature of the exhaust gas is kept just above its dew point temperature. Classification based on configuration (1)

(1) long route system (LR): In an LR system the pressure drop across the air intake and the stagnation pressure in the exhaust gas stream make the EGR possible. The exhaust gas velocity creates a small stagnation pressure, which in combination with low pressure after the intake air, gives rise to a pressure difference to accomplish EGR across the entire torque/speed envelop of the engine.

(2) Short route system (SR): These systems differed mainly in the method used to set up a positive pressure difference across the EGR circuit. Another way of controlling the EGR-rate is to use variable nozzle turbine (VNT). Most of the VNT systems have single entrance, which reduce the efficiency of the system by exhaust pulse separation. Cooled EGR should be supplied effectively. Lundquist and others used a variable venturi, in which EGR-injector was allowed to move axially, thus varying the critical area was used (Lundquist et al 2000). Classification based on pressure (1) Two different routes for EGR, namely low-pressure and high-pressure route systems may be used (Kohketsu et al 1997). (i) Low pressure route system: The passage for EGR is provided from downstream of the turbine to the upstream side of the compressor. It is found that by using the low pressure route method, EGR is possible up to a high load region, with significant reduction in NOx. However, some problems occur, which influence durability, prohibitionary high compressor outlet temperature and intercooler clogging.

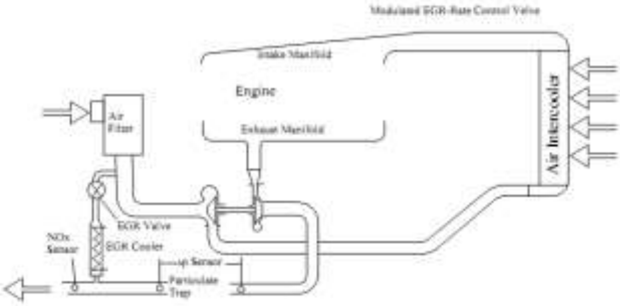


Fig. 2: Low Pressure Route EGR System (9)

(2) High pressure route system: The EGR is passed from upstream of the turbine to down-stream of the compressor. In the high pressure route EGR method, although EGR is possible in the high load regions, the excess air ratio decreases and fuel consumption increases remarkably.

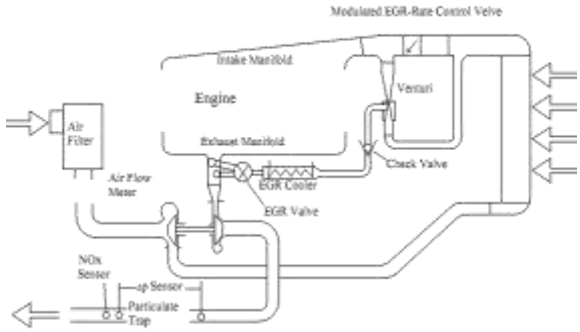


Fig. 3: High Pressure Route EGR System (9)

1) EGR Cooler

The EGR cooler can be simply a heat exchanger in which the temperature of exhaust gases is reduced by the coolant from the cooling system of the engine. The EGR cooler comes in different forms the most common type is shell and tube shown in fig. 3. EGR cooler consist of shell and tube, exhaust gases pass through tube side and coolant from shell side. The effectiveness of shell and tube and stack type EGR coolers is investigated by Kim (2008) and he found that stake type has 20- 25 % higher effectiveness than shell and tube type (11). There are various type of EGR coolers designed to increase their effectiveness like EGR coolers with different type of tube fins (rectangular, triangular, dimple, circular) because of this surface area of cooler is increased and heat transfer is increased and thus effectiveness is increased.

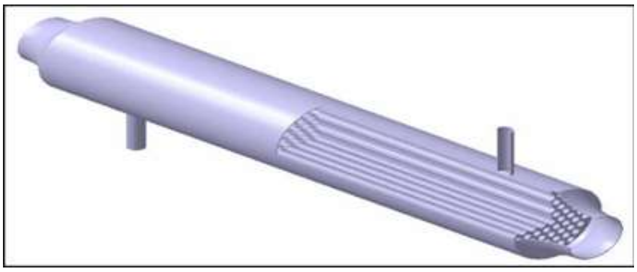


Fig. 4: EGR Cooler CAD Model

E. CFD's working-

The most fundamental consideration in CFD is how one treats a continuous fluid in a discretized fashion on a computer. One method is to discretize the spatial domain into small cells to form a volume mesh or grid and then apply a suitable algorithm to solve the equations of motion (Euler equations for inviscid and Navier-Stokes equations for viscous flow). It is possible to directly solve the Navier-Stokes equations for laminar flows and for turbulent flows when all of the relevant length scales can be resolved by the grid (a direct numerical simulation) (2).

1) Basic Approach to using CFD [2]

Pre-processor: Establishing the model

- Identify the process or equipment to be evaluated.
- Represent the geometry of interest using CAD tools.
- Use the CAD representation to create a volume flow domain around the equipment containing the critical

Flow phenomena.

- Create a computational mesh in the flow domain.

Solver:

- Identify and apply conditions at the domain boundary.
- Solve the governing equations on the computational mesh using analysis software.

Post processor:

- Interpreting the results Post-process the completed solutions to highlight findings
- Interpret the prediction to determine design iterations or possible solutions, if needed.

Governing Equations

Each CFD software package has to produce a prediction of the way in which a fluid will flow for a given situation. To do this the package must calculate numerical solutions to the equations that govern the flow of fluids. For the analyst, it is important to have an understanding of both the basic flow features that can occur and so must be modeled and the equations that govern fluid flow. The physical aspects of any fluid flow and heat transfer are governed by three fundamental principles

Continuity equation
Momentum equation
Energy equation

2) Application of CFD

CFD not just spans on chemical industry, but a wide range of industrial and nonindustrial application areas which is in below

(1) Aerodynamics of aircraft and vehicle.
(2) Combustion in IC engines and gas turbine in power plant.
(3) Loads on offshore structure in marine engineering.
(4) Blood flows through arteries and vein in biomedical engineering.
(5) Weather prediction in meteorology.
(6) Flow inside rotating passages and diffusers in turbo-machinery.
(7) External and internal environment of buildings like wind loading and heating or
(8) Ventilation system.
(9) Mixing and separation or polymer moldings in chemical process engineering.

F. Effect on performance of EGR cooler with different type of tubes

The EGR cooler significantly cools down the hot exhaust gases at temperatures ranging from 300 to 100^{o}c reduction of combustion chamber temperature as well as NOx emission from diesel engine.

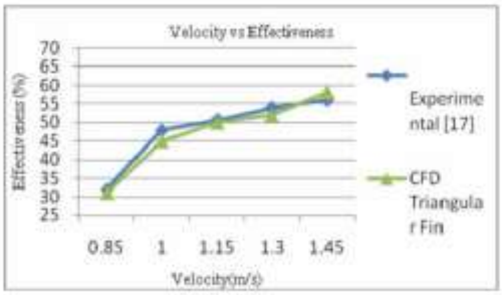
H.M KIM discussed about the effectiveness and other parameter of different type of EGR cooler with different type of tubes like plain tube and spiral tube. In this investigation he found out that the spiral tube is more efficient than plain tube in both engine test and numerical analysis results (14).

Comparison of results for different type of EGR cooler (14)

	Numerical analysis efficiency (%)	Experimental efficiency (%)
Plain tube	50.4	49.8
Spiral tube	63.2	56.8

Swapaneel sarma discussed about the triangular fins which is attached to tube along the tube length. Tube material is take as mild steel. He carried out analysis to find the effectiveness and tube side overall heat transfer coefficient by varying the tube side fluid velocity and shell side velocity kept constant (2).

He found out that effectiveness of EGR cooler is increased as we increased velocity of fluid. Heat extraction rate also increased between coolant and hot gases.



Comparison of effectiveness and velocity (2)

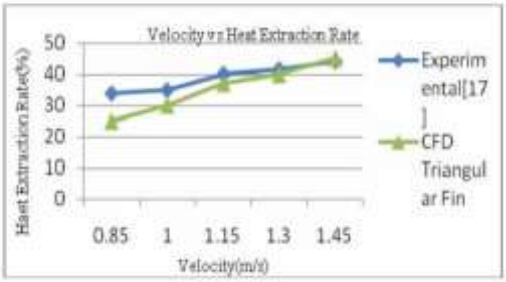


Fig. : Comparison of Heat Extraction Rate and Velocity (2)

The continuous helical baffles when designed well can prevent the flow induced vibration and fouling in the shell side. Similar results on fouling were reported by Murugesan and Balasubramanian4. The experimental study of Shell and Tube Heat Exchangers with the use of continuous helical baffles can result approximately ten per cent hike in heat transfer coefficient in comparison with that of traditional segmental baffles for the same shell side pressure decline (15). By changing the inclination of baffle from 0^o to 20^o Arjun K.S plotted CFD graphs of temperature distribution and velocity and concluded that heat transfer rate has increased.

Heat transfer rate along tube side (15)

II. CONCLUSION

We reviewed various aspects related to the operation of EGR coolers in diesel engine which are installed to achieve compliance with emissions regulations. EGR coolers are designed in the different ways to increase the performance of them to reduce the engine emissions. There are various type of EGR cooler design are used in the diesel engine to increase the surface area such as EGR cooler with spiral tube, EGR cooler with rectangular fin tube, EGR cooler with triangular fin tube, and because of this heat transfer rate would increase and the effectiveness of EGR cooler will increase. CFD tool has been used for performance analysis of the EGR cooler and experimental results are compared with CFD results. CFD provides the flexibility to change design parameters without the expense hardware changes. It therefore costs less than laboratory or field experiments, allowing engineers to try more alternative designs than would be feasible otherwise. In the continuation of my project I would make changes in the design of EGR cooler and analytically calculate the performance of EGR cooler and these analytical results will be compared with CFD results.

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