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A Review : Exhaust Gas Recirculation Mixer for Diesel Engine

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ABSTRACT

In internal combustion engine exhaust gas recirculation (EGR) an emission control technology allowing significant NOx emission reductions from most types of diesel engines from light-duty engines through medium- and heavy-duty engine applications right up to low-speed, two-stroke marine engines. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. This dilutes the O2 in the incoming air stream and provides gases inert to combustion to act as absorbents of combustion heat to reduce peak in-cylinder temperatures. NOx is produced in a narrow band of high cylinder temperatures and pressures. The exhaust gas recirculation system requires a mixing device to combine the recirculated exhaust gas and the charge air from the charge air cooler. The mixer insures an equal mixture of recirculated exhaust gas and fresh charge air to all cylinders. In this paper, an attempt is made to review the literature on various EGR mixer design concepts and its effect on cylinder to cylinder EGR distribution with the help of simulation tools and experimental results.

Keywords— Exhaust Gas recirculation, Particulate matter, Oxides of nitrogen, EGR Valve, EGR mixer

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I. INTRODUCTION

Over past 15-20 years more stringent legislation has been imposed on NOx, smoke and particulate emissions emitted from automotive diesel engines. Future emissions regulations like BSIV and above in India, Diesel engine manufacturers are forced to find complex ways to reduce exhaust gas pollutant emissions, in particular NOx and particulate matter (PM).In diesel engines, it is highly desirable to reduce the amount of NOx in the exhaust gas. NOx formation is a highly temperature dependent phenomenon. Therefore, in order to reduce NOx emissions in the exhaust, it is necessary to keep the peak combustion temperatures under control. One efficient way for ensuring this is by Exhaust Gas Re-circulation (EGR). EGR involves diverting a fraction of the exhaust gas into the intake manifold where the recalculated exhaust gas mix with the incoming air before being inducted into the combustion chamber. The EGR system reduces NOx emissions by introducing concentration of the exhaust gas into the combustion chamber to increase the heat capacity of mixture hence lower the temperature of burning gases reduce the NOx emission. As EGR would result in the combustion lag and reduced the temperature, there is also a possibility that HC, CO, and PM emission would increase [1,6-7].

Engine having EGR emission system where homogeneously exhaust gas mixes with fresh intake charge is very important from the emission & engine fuel consumption point of view. Proper exhaust gas mixing and distribution across cylinder to cylinder will lead to robust engine exhaust gas emission control. It is very important in inline multi-cylinder engine that EGR distribution across all cylinders should be uniform. Improper charge (i.e. Fresh air +EGR) distribution leads to uneven charge combustion and unpredictable exhaust emission. Therefore, to achieve the best power performance of engine and the lowest emissions, it is required to figure out a proper EGR rate in each cylinder, by using EGR mixture techniques with EGR system [5].

II. LITERATURE REVIEW

Exhaust Gas Recirculation System

Exhaust gas recirculation (EGR) is a technique by which a portion of engine's exhaust is returned to its combustion chamber via its inlet system. This method is designed to extract heat from the combustion process, thus lowering its temperature and reducing NOx.

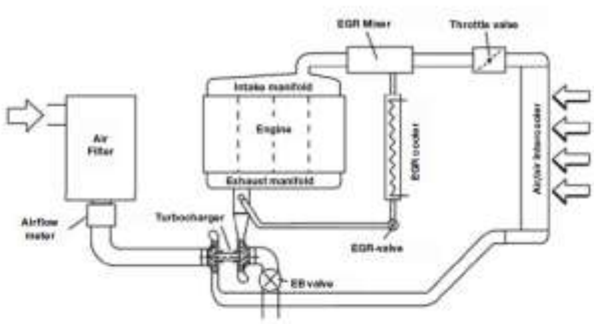

Fig.1 Cooled EGR HD Engine Layout [1]

This method also involves displacing some of the oxygen inducted into the engine with its fresh charge air, thus reducing the rate of NOx formation. EGR system has the following instruments.

1) EGR cooler - EGR cooler is required to reduce the temperature of the exhaust gas before introducing it into the combustion chamber, so overall temperature of the mixture of exhaust gas and fresh air inside the cylinder is reduced. The temperature inside the combustion chamber is directly related to the NOx produced.so less amount of NOx will be produced.

2) EGR valve -EGR valve is used to vary the amount of exhaust gas into the cylinder. percentage of EGR affects the engine exhaust parameters like oxides of nitrogen (NOx),oxides of carbon (CO and CO2) hydrocarbons(HC) and particulate matter(PM).percentage of EGR also affects the engine performance parameters like brake specific fuel consumption, volumetric efficiency, thermal efficiency etc.

3) EGR Mixing Device (Mixer) - The exhaust gas recirculation system requires a mixing device to combine the recirculates exhaust gas and the charge air from the charge air cooler. The mixer insures an equal mixture of recalculated exhaust gas and fresh charge air to all cylinders.

Definition of EGR rate

The amount of reintroduced exhaust gas is usually expressed relative to the total (diluted) charge air flow rate and referred to as EGR rate. We can calculate EGR rate based on volumetric basis or mass basis-both definitions are commonly used for calculating EGR rate [1]. On a mass basis, the EGR rate is:

EGR Mass % =
[(mEGR intake) / (mfresh air + mintake)]*100 (1)

Where, mEGR is the mass flow rate of EGR, and mAir is the mass flow rate of fresh air.

Equation (1) is considered as a volumetric basis EGR mass flow. Fresh air & exhaust gases contain nitrogen particles and density difference occurs as nitrogen is less than 1%. EGR rate to be calculated by common technique is to measure amount of intake CO2 discharge in intake system with fresh charge to produced exhaust CO2 during combustion process. The ratio will provide the volumetric EGR rate:

EGR [%] =
[(Inlet CO2 – Ambient CO2)/(Exhaust CO2 – Ambient CO2)]*100 (2)

EGR Rate = [(Inlet manifold CO2/ Exhaust CO2)] * 100 (3)

Or possibly

EGR Concentration = [(Inlet manifold CO2 – Ambient CO2) / (Exhaust CO2 – Ambient CO2)] (4)

EGR Mixer Design & its effect on distribution of EGR

Hardik Lakhlani et al. [1] studied the influence of EGR mixture design and its effect on distribution across the cylinder has significant impact on the NOx-PM trade-off which is studied on light duty direct injection diesel engine. A simulation and experimental study of EGR mixer design is conducted to explain this effect and the distribution of EGR across the cylinder at different EGR flow rate. Experiments have been conducted on an engine test bench with and without air-EGR mixer and demonstrated that variations in cylinder-to cylinder EGR distribution results in a deteriorated NOx-PM trade-off (increased NOx emission level at a given PM emission level, or increased PM emission level at a given NOx emission level) as compared to the well mixed with EGR mixture configuration with equal EGR rate for all the cylinders. The aim of this study is to show that EGR mixture effect & cylinder-to-cylinder variations in EGR can lead to higher NOx and PM emissions as compared to a configuration where the EGR is equally distributed amongst all cylinders. The influence of the NOx-PM trade-off has been experimentally studied in details. The impact of EGR on smoke at high load is particularly detrimental because the engine is already working at low air fuel ratio. In such condition, improper charge distribution across cylinder inversely effects on NOx & PM emission tread.

David B. Roth et al. [2] presented the system design concept and engine test results of the prototype mixer. A gasoline engine, and to a greater extent a spark ignition engine running on Natural Gas, will encounter enough water condensation at some steady-state conditions to damage the compressor wheel due to the high-speed collision between the compressor blades and the water droplets. As an alternative to not utilizing beneficial EGR at the condensing conditions, the team at BorgWarner has developed a LPL EGR mixer that is effective at condensing and collecting the water droplets and routing the water around the compressor wheel. The new Condensing EGR mixer was developed from the known concept of utilizing a mild venture section to enhance EGR delivery and mixing. The developed system was designed to both maximize condensation and separation of liquid water from the EGR stream, as well as manage its disposal through the engine in a manner that both avoids damage to the compressor and minimizes liquid freezing potential in very low ambient conditions. The system architecture includes a Mid-Pressure path that is utilized to both purge the system of liquid water as, well as provide engine efficiency improvements at moderate load operation points compared to utilizing pure LPL EGR.

Oldřich Vítek et al. [3] studied different EGR solutions. This paper compares 4 different EGR systems by means of simulation in GT-Power. The demands of optimum massive EGR and fresh air rates were based on experimental results. The experimental data were used to calibrate the model and ROHR, in particular. The main aim was to investigate the influence of pumping work on engine and vehicle fuel consumption (thus CO2 production) in different EGR layouts using optimum VG turbine control. These EGR systems differ in the source of pressure drop between the exhaust and intake pipes. Firstly, the engine settings were optimized under steady operation – BSFC was minimized while taking into account both the required EGR rate and fresh air mass flow. Secondly, transient simulations (NEDC cycle) were carried out – a full engine model was used to obtain detailed information on important parameters. The study shows the necessity to use natural pressure differences or renewable pressure losses if reasonable fuel consumption is to be achieved.

S. Karthikeyan et al. [4] this paper emphasizes use of Computational Fluid Dynamics (CFD) technique for evaluating the effectiveness of an intake system design for homogeneous mixing of Exhaust Gas Recirculation (EGR) with fresh air inside the intake system i.e. inlet-manifold and duct. Modern diesel engines are commonly, in such case proper mixing will take place only when the turbine upstream pressure is sufficiently higher than the boost pressure. In case the pressure difference is not enough to meet the engine requirements an alternate solution should be arrived by either increasing the turbine upstream pressure or reducing the boost pressure locally by providing the obstruction in the air flow passage inside the duct without affecting the engine performance. As a part of this study, five different novel concepts for air and EGR mixing is analyzed computationally to meet the above requirement. From the five different concepts the optimized inlet manifold with larger injection area and half bluff body concept has given increase in the air and EGR mixing rate computationally. Therefore by using this concept the smoke level is experimentally investigated on the engine test bench for different load conditions.

S. Reifarth et al. [5] studied importance of the pulses present in the EGR-flow. By simulation in 1-D and 3-D as well as by a fast measurement method, it is shown that the EGR is transported in the air flow in packets. This implies that the timing between intake valve opening and the positioning of the EGR packets has a high influence of the distribution of EGR between the cylinders. It was proven that the EGR and air move in the flow direction in packets. This could be shown by 1-D and 3-D simulation models and by time resolved measurements. As a consequence of this, the cylinder distribution of EGR is not only dependent of the mixing across the cross-section in the mixing point but also of mixing in flow direction. 1-D simulation models can be used to analyze the influence of the pulsating concentration in the pipes shortly after the mixing pipe. In order to do so, the discretization length of the model needs to be shortened drastically. Even though the mixing over the cross-section needs to be simulated and optimized by 3-D simulation, the timing of the pulses and their amplitude in the mixing point can be simulated and understood to a large extend by 1-D simulation. This can help to decide whether a detailed 3-D analysis is needed in a certain case or not.

Susumu Kohketsu et al. [6] in these study three EGR methods were applied to a 12 litter turbocharged and intercooled Dl diesel engine and the exhaust emission and fuel consumption characteristics were compared. One method is the Low Pressure Route system, in which the EGR is taken from downstream of the turbine to the compressor entrance. The other two systems are variations of the High Pressure Route system, in the EGR is taken from the exhaust manifold to the intake manifold. One of the two High Pressure Route EGR systems is with back pressure valve located at downstream of the turbine and the other uses a variable geometry (VG) turbocharger. It was found that the High Pressure Route EGR system using VG turbocharger was the most effective and practical. With this method the EGR area could be enlarged and NOx reduced by 22% without increase in smoke or fuel consumption while maintaining an adequate excess air ratio. For effective EGR and NOx reduction of a turbocharged and intercooled diesel engine, problems of the compressor and the intercooler can be avoided by using a VG turbocharger and High Pressure Route EGR method.

Reza Rahimi et al. [7] presented the results of numerical and experimental investigations to evaluate the distribution of exhaust gas recirculation (EGR) between cylinders in a DI turbocharged diesel engine. The turbulent three-dimensional flow field was analyzed by the numerical solution of conservation equations with an appropriate turbulence model. EGR was applied to intake manifold with various rates at cooled and non-cooled states. The experiments were conducted on an MT4.244 turbocharged DI diesel engine under full load condition at 1900rpm. The results were obtained as EGR distribution is equal between cylinders for low EGR rates in hot and cooled cases and Cooled EGR shows better EGR distributions compared to hot EGR particularly at high EGR rates. Equal EGR distribution results in an improvement in performance and reduction NOx and PM emissions when compared to non-well-mixed air and EGR gases.

SUMMARY AND DIRECTION FOR FUTURE WORK

It can be summarized that a common issue has been analysed in several studies concerns the cylinder-to-cylinder distribution of EGR. As the emission formation in a cylinder is sensitive to variations in the EGR-rate, an even distribution of EGR between all cylinders is desirable. If one cylinder receives more EGR than the others it produces more PM, if it gets less EGR the NOX emissions of this cylinder increase. An uneven distribution can therefore increase the total engine out emissions as compared to an engine where all cylinders receive an equal amount of EGR.

Future combustion systems such as low-temperature combustion have been shown to react more to uneven distribution than conventional diesel combustion, making this issue important for the future. Several studies shows with EGR mixture mixing of fresh charge leads to lower soot emission with almost same or less NOx at mid and higher engine speeds. The significant soot reduction can be observed at higher load conditions with the help of EGR mixture. The massive EGR combined with the possibilities of the common-rail fuel injection system allowing advanced cold flame combustion patterns at engine low load has great potential to solve current diesel engine problems by maintaining good fuel efficiency and low CO2 emission level.

Various Researchers after undergoing study of various EGR mixer design with the help of experimental and simulations concluded that the more homogeneous EGR gas and air mixture effects lower NOx levels due to evolved uniform cylinder-to-cylinder EGR rate distribution. The mixture homogeneity is an important parameter of the EGR mixer. It has been reviewed that Venturi section EGR mixer and EGR injection with larger area and bluff body concept enhances EGR flow rate and EGR air mixing. CFD simulations give an insight into the main behaviour of EGR mixers and help to elaborate the most important criteria, which are required for a successful mixer design selection. For effective EGR and NOx reduction of a turbocharged and intercooled diesel engine, problems of the compressor and the intercooler can be avoided by using a VG turbocharger and High Pressure Route EGR method.

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