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Investigation of the Combustion of Exhaust Gas Recirculation in Diesel Engines with a Particulate Filter and Selective Catalytic Reactor Technologies for Environmental Gas Reduction

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Investigation of the combustion of exhaust gas recirculation in diesel engines with a particulate filter and selective catalytic reactor technologies for environmental gas reduction

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ABSTRACT

The use of diesel engines has increased dramatically in recent years, as has the number of exhaust emissions. These emissions have the potential to endanger Mother Nature and the living species within it. Governments all over the world have introduced legislative rules on exhaust emission reduction in order to limit the number of emissions released into the environment through the use of global sustainable development technologies. This has compelled automobile manufacturers to create a variety of diesel emission reduction systems, the most important of which are the Diesel Particulate Filter (DPF), Exhaust Gas Recirculation (EGR), and Selective Catalytic Reactor (SCR). The primary goal of this research work is to reduce diesel engine exhaust gas emissions by utilizing emission reduction systems such as DPF, EGR, and SCR. Here, various combinations of the aforementioned emission reduction systems were tested to determine the best possible combination that had the greatest impact on the exhaust gases. The best possible combination depends on the performance of what gases are to be eliminated, keeping the EGR rate at an optimum value between 10% and 20%. If preference is given to reduce NOx, then we will combine 10–20% EGR with SCR, but if the preference is given to reduce HC, CO, and soot, we will use 10% - 20% EGR in combination with a DPF. Overall, the DPF + SCR with 10% EGR rates seems to be an appreciable result.

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1. Introduction

The Diesel Engine, invented by the German engineer Rudolf Diesel, was a marvelous creation that changed the way the automobile industry worked. It is an internal combustion engine that compresses air to elevate its pressure and temperature so high that the atomized diesel fuel undergoes combustion almost instantaneously when it is sprayed into the combustion chamber. The Major advantage of a Compression Ignition (CI) engine compared to a Spark Ignition (SI) engine is the higher compression ratio achieved in the former, making it more efficient. This makes diesel engines more suitable for heavy-duty vehicles, which require more torque to overcome rough terrain. In a 4-stroke Diesel engine, a certain mass of air is taken in through the inlet valve into the combustion chamber as the piston in the cylinder moves towards the Bottom Dead Center (BDC). At the BDC, the piston reverts its direction to compress the air inside the cylinder to very high pressure and temperature. The compression ratio values may range from 15 to 20 in a typical CI engine. The diesel fuel is then sprayed in an atomized form just before the piston arrives at the Top Dead Center (TDC) to account for the ignition delay. The high temperature and pressure of the air cause the fuel to ignite almost spontaneously, forcing the piston to move back toward the BDC. This is known as the power stroke of the engine, as it is where the engine provides the necessary torque to move the vehicle. In the last stroke, as the piston moves back up, the exhaust valve is opened to let out all of the exhaust gases. The intake valve opens again to take in a fresh charge of air, and the cycle is repeated so on. Heavy road trucks, ships, many buses, many commercial boats, heavy tractors, military vehicles, passenger cars, many large vans, large-scale portable generators, many agricultural and mining vehicles, and many long-distance engines use the majority of diesel engines.

1.1. Exhaust gas recirculation (EGR)

The EGR is a method used nowadays in the automotive industry to reduce the Oxides of Nitrogen (NOx). The nitrogen oxides are released by the engine during the operational period due to high combustion temperature. A high concentration of NOx is formed when the combustion temperature exceeds temperatures of 2400–2500 °C. The main principle of the EGR system works by recirculation of a small amount of exhaust gas back into the combustion chamber via the intake manifold. This small amount is combined with the incoming air/fuel charge. By this method, the high temperatures are minimized by diluting the air/fuel mixture. The Exhaust gas recirculation flow comprises 3 different working conditions. The first condition is a high flow which is essential for mid to increasing/cruising accelerating ranges. The combustion temperature is considerably high here. The 2nd requirement is the low EGR flow. This kind of flow is needed for low speeds and lesser loading conditions. The 3rd condition is no flow condition. No flow should occur when the engine is slightly warming up, and the throttle is idle. Therefore, these three operations through which the EGR takes place can have a considerable impact on vehicle efficiency/derivability. As stated above, the EGR mainly works on recirculating a small portion of the exhaust gas back into the combustion chamber. Firstly, the air mixture is brought into the cylinder. The supply of the exhaust gas is completed. The use of EGR is needed for NOx emission control. Having discussed the working principle of Exhaust Gas Recirculation, the following are the main factors by which the target pollutant NOx is controlled:

- The heat capacity (Cp) of air is lower than that of the exhaust gas. Thus, there will be a small number of energy releases during the combustion, and the lower limit of the temperature increases.
- The partial pressure of oxygen is reduced; thus, the concentration of oxygen inside the cylinder also goes down. This is because of the replacement of the combustion mixture with an exhaust gas with a lower proportion of oxygen.
- The speed at which the combustion is taking place is also reduced, and the lower limit of temperature rises as a result.

If the combustion temperature is way too high, the formation of NOx takes place. Any attempt to reduce the NOx. The implementation of the EGR will increase the particulate matter in the loading oil. The re-introduction of exhaust gas that is acidic in nature will increase the Total Acidic Number (TAN) of the lubricant.

1.1.1. Theory of operation

The main function of an EGR method is to control the flow under different working conditions. It also has to override flow which would otherwise compromise the performance of the engine. As the load changes the engine, the amount of exhaust that must be supplied into the intake manifold changes. The result is an operational system working on a thin line between the performance of the engine and the control of NOx. Again, too much metering of the exhaust gas can lead to a decline in engine performance. The knocking of the engine can occur if the emission standards are not met and there is little EGR flow. The EGR ratio is defined as the theatrical volume of recirculated exhaust gas.

1.1.2. EGR cooling system

The exhaust gas that has been recirculated should be cooled down. 50% of the reduction of the radiators is possible if the design is followed accordingly. Cooling down the recirculated gas is one of the ways to reduce the emission levels which cause pollution. The generation of NOx can be reduced by decreasing the temperature of the gas in the combustion chamber. An EGR cooler is installed between the valve and the intake manifold. Water is used as the cooling medium and has proven to be very effective than using air. The heating time for quick warm-up of after-treatment devices has been demonstrated to decrease in a system with a controlled EGR cooling system, improving engine temperature control. The amount of air entering the combustion chamber is increased by the intake of the cooled EGR system, which also makes the air denser. Thus, complete combustion is accomplished, which lowers the number of particles produced.

1.2. Diesel particulate filter (DPF)

A DPF, short for DPF, is a device that can be fitted to the exhaust section of an automobile to reduce the number of soot particles/

Particulate Matter which is released into the atmosphere. It does this so by filtering the exhaust gases out and, in the process, traps the Particulate Matter (PM). A DPF consists of an enclosed structure that contains a certain type of filter to trap that particulate matter. It can also consist of a burner in order to burn the soot in a process called regeneration. Different types of Filters can be found within the DPF, all designed to similar requirements. A good DPF filter should be able to;

- Carry out fine filtration
- Creates a Minimum Pressure drop
- Cost low
- Should be durable to withstand the rough conditions

Some of the filters used in the DPF include;

- Cordierite wall flow filter: This is one of the most common types of filters used in DPFs. They are cheap, easy to install, and provide exceptional filtration efficiency. The major drawback of this system is that it is not durable as its melting temperature is low (about 1200 °C). Some of the filters have melted off during the regeneration process due to their low temperature.
- Silicon Carbide wall Flow Filter: This type of filter is made by joining many small silicon carbide segments together to form one big piece. The advantages of this type of filter are similar to the ones listed above, except that the melting temperature of a silicon carbide wall flow filter is about 1000 °C higher than the common Cordierite wall-flow filter.
- Metal Fibre flow through the filter: The filters made from this type of material consist of metal wire-like fibers knitted together to form one large monolith. Such types of filters are expensive compared to the former two. The major advantage of this type of filter is that, even at a low temperature, electric current can be passed through the filter to perform the regeneration process.

1.2.1. Working on a DPF

The Exhaust gasses from the engine combustion chamber are made to pass through the DPF, which can be fitted either before or after the catalytic converter based on preference. The exhaust gases flow through the porous holes in the filter. The soot particles are larger than the porous holes of the filter; hence they get trapped as they pass through the filter. The treated exhaust gases then pass through the exit of the DPF out into the atmosphere. The soot particles Accumulate slowly inside the filter till the backpressure reduces to a certain minimum value, after which the differential pressure sensor sends a signal to the Electronic Control Unit (ECU). The ECU then sends a signal to the burner to carry out the regeneration process. In the regeneration process, the accumulated soot is burnt off in any of the following ways;

Active regeneration- After the particulate build-up reaches a certain level, the exhaust gas temperature is increased to above 600°. The temperature can be increased by engine throttling, the use of a burner upstream, and electrical regeneration.

- In engine throttling, the air-fuel mixture is made leaner to increase the amount of oxygen available for combustion. This causes the exhaust gases to be at a higher temperature which may then burn off the accumulated soot.
- A burner may be employed such that whenever a signal is given to it by the ECU, it can combust the accumulated soot around the filter.
- Electric regeneration is specifically for the ones containing a metal fiber flow through a filter. Electricity is passed through the filter, which heats and burns the unwanted soot.

Passive regeneration-these systems employ a catalyst that reduces the overall oxidation temperature of the soot particles to the level of exhaust gas temperatures. By reducing the oxidation temperature, the soot can easily be regenerated at lower temperatures.

1.3. Selective catalytic reduction (SCR)

The selective catalytic reduction, also known as SCR, is one of the effective ways of incorporating the conversion of NOx with the help of catalysts in Nitrogen (N_2) and Water (H_2O). Mostly a reductant in its gaseous form is mixed with exhaust gas and adsorbed onto a catalyst. The by-product of the reaction is Carbon Dioxide (CO_2) if the reductant used is urea. The SCR of NOx with the usage of ammonia as the reducing agent was first developed in the United States by the Engelhard Corporation in 1957. The advancement in this technology was spread in Japan and US in the early 60s, with the primary emphasis being on low-cost catalyst agents. The first real-time large-scale Selective catalytic reduction unit was installed by the IHI Corporation in 1978.

The major applications of SCR are found in boilers (industrial and utility) and importantly in municipal units to reduce solid waste. This has been effective to an extent (70–95%) reduction. In recent years automobiles have been using this technology, as well as gas turbines and locomotives.

1.3.1. Chemistry of the process

The reduction reaction of NOx takes place with the influx of gas via the catalytic chamber. First, a reductant like Urea is mixed with the other gas components before passing through the catalytic chamber. The reaction carried out in the SCR is as follows.

$$4NO + 2(NH_2)_2CO + O_2 \rightarrow 4N_2 + 4H_2O + 2CO_2$$

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O_2$$

$$NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

The secondary reactions are as follows:

$$2SO_2 + O_2 \rightarrow 2SO_3$$

$$2NH_3 + SO_3 + H_2O \rightarrow (NH_4)2SO_4$$

The following is the reaction is when urea is used instead of aqueous ammonia.

$$NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4$$

The most preferred temperature to carry out the reactions is in the range of 600–700 K, but the range can be increased with longer reaction times. The various factors which affect the minimum temperature for the reaction are the components of the gas and the geometrical structure of the catalyst. An alternative reductant commonly used is Ammonium Sulphate. The catalysts used in selective catalytic reduction are derived from ceramics, mainly used as a carrier and oxides of metals such as Tungsten and molybdenum. Recently activated carbon has been used to develop a catalyst. This helps in the depletion of NOx at lower limits of temperatures as well. Each catalyst has its advantages and disadvantages. The base metal catalysts do not possess sufficient thermal durability but are budget-friendly and are functional in temperature limits mostly seen in the power plants and boilers. Thermal durability is an important factor when the combination of SCR and DPF is used in automobile applications. Especially with forced regeneration, the base metal catalysts have a high potential of being catalyzed, which in turn can oxidize SO_2 to SO_3 and can cause considerable damage. Another commonly used catalyst is the Zeolite catalyst, with the main advantage being the operation at elevated temperature ranges, which the base catalysts lack. They possess the ability to sustain operations carried out at temperature ranges of 900 K–1100 K. Also, the probability of damage from SO_2 oxidation is much lesser.

1.3.2. Reductants

With catalysts, the different reductants being incorporated in the Selective catalytic reduction applications are urea and ammonia in aqueous form. These are widely available. The purest form of anhydrous ammonia is toxic and safe storage is not feasible. The biggest advantage being no further conversion is required when used in the SCR. Large industries are in favor of this and are used by industrial operators. Compared to anhydrous ammonia, ammonia in an aqueous form is relatively safe for storage and transport. Urea is the safest when it comes to storage, but thermal decomposition is required for further conversion to be used as a feasible reductant.

2. Literature review

The different areas of research that have taken place to reduce diesel emissions will be cited in this chapter. The main focus will be put on diesel emissions, the reduction systems such as the Diesel Particulate Filter, Selective Catalytic Reactant, and Exhaust gas recirculation. The different studies that have taken place on both the emissions and the reduction systems led us to the objectives of our detailed study.

The authors studied the various exhaust gases from diesel engines at various loads. They described that among the pollutant emissions, Carbon Monoxide (CO) and Hydrocarbons (HC) are emitted due to incomplete combustion and unburned fuel, but NOx emissions occur due to high combustion temperatures above 1600 °C. About PM emissions, the reason for PM emissions is the agglomeration of partially burned fuel, partially burned lubricant, fuel oil, and cylinder lubricant [1]. The author has described the parameters of the Emission of various oxides of nitrogen concerning temperature and their control. He briefly looked at the history of emission reduction at a glance. He concluded that NOx emissions should be reduced immediately and effectively since the level is still serious and an issue. The level of Euro-VI is set to 0.08 g/km now, a phenomenal 55% reduction from the current Euro-V standard for passenger cars and 75% in the case of a large car. This study was done based on the Euro-VI General Standard and Euro -V standard [2]. The researcher has carried out repeated investigations and has concluded that the injection of solutions in the aqueous form (urea) in the exhaust manifold for NO reductions is an age-old technology, at least 2 decades old. Since then, many methods have been developed which have been commercially viable. Urea solution of varying concentrations from 10 to 30% with variable flow rates was tested by using vanadium as a catalyst which improves the rate of the chemical reaction even at the lower limit of the temperatures of even 190 °C Results showed that a maximum of 26.41% of NOx reduction was achieved with a regulated flow rate of 0.76 lit/hr. with 9% urea concentration [3]. The authors have studied that carrying out the SCR technique using urea as the primary agent is an optimum method for application on stationary diesel engines. The journal talks about the fundamental drawbacks and challenges of extending the Urea-SCR applications to the mobile domain. The steps involved in the reduction process included the endothermic decomposition of liquid urea, hydrolysis of the isocyanic acid, and a selective reduction of NOx [4]. The authors have done experiments and investigations on the performance characteristics, combustion, and emission characteristics of SI engines with blends of cotton seed oil of 20%, 40%, 70%, and 100% in volume. There was an increase in the oxides of nitrogen compared to the diesel in its homogeneous form; the SCR system was implemented in the exhaust pipe. The results showed that with the injection of a 30% concentration of urea solution, there was a rapid decrease in the rate of the number of oxides of nitrogen [5]. The usage of Pongamia pinata methyl ester (PPME) as a substitute fuel for diesel engines has been researched by the authors. For the reduction of nitrogen oxides, aqueous urea solutions were injected into the tail end of a diesel engine's pipe along with PPME. Four different observations were made for the various concentrations of urea solution 0%, 10%, 20%, and 30% by mass, along with various rates of flow of urea solution as the reductant, which enhances the chemical reactions. With a urea flow rate of 0.58 lit/hr, 25% concentration of urea solution and marine ferromanganese nodule, 62% NOx reduction was attained [6]. The survey on NOx treatment is major in the present years due to rising environmental awareness. Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR) are the proven technology for reducing NOx. The other treatment methods offer higher NOx. The authors have investigated the effect of EGR (10%, 15%, 20%, and 25%) on 3 cylinders, constant speed, and air-cooled CI diesel engine, from this investigation they have concluded that at lower loads the higher rate of EGR can be applied to CI engine without any drawback of its fuel economy and efficiency, thus the NOx reduction is attained [7]. The authors have proved that EGR combined intake heating promisingly reduces the total hydrocarbon emission with an enhancement of BTE at lower load conditions [8]. The EGR was employed in an indirect injection spark ignition engine and showed to be more efficient in terms of fuel economy [9,10]. By using Methanol blended fuels, the adjustment of exhaust port parameters has a greater impact on mean indicated pressure, trapping efficiency, and scavenging efficiency [11]. The study's conclusions state that innovative coal-fired units should be adopted and their performance pledged at a range of loads, including minimal loads. To increase efficiency and lower carbon dioxide emissions, Vietnam should employ ultra-supercritical technology in new units [12]. Variable valve actuation (VVA) can be an effective approach to boost performance while reducing emissions by raising the in-cylinder charge temperature [13]. The developed multivariable engine controller's performance is demonstrated on a six-cylinder diesel-E85 RCCI engine. In comparison to open-loop control, the stable and safe operating range is increased from 25 to 35 °C intake manifold temperature, and the ultimate load range is increased by 14.7% up to BMEP = 14.8 bar [14]. Due to better performance and emission characteristics, B20 mahua biodiesel at 8 lpm of biogas flow rate in dual fuel mode is determined to be the best combination [15]. SCR creates a substantial reduction in the correlation coefficients between NOx emissions and air-fuel ratio (0.76 vs 0.47 for China V truck; 0.72 vs 0.05 for China VI truck), although not in the correlation coefficients between CO2 emissions and air-fuel ratio, which can be used to determine whether SCR is working effectively [16]. The SCR reaction was shown to proceed proficiently via either surface NH_3 or NH_4 species, attempting to solve a long-standing debate about their involvement in the SCR reaction [17]. Managing active DPF regeneration must consider the effect of the fast regeneration time frame on emission and input energy, as well as the influence of flow rate and regeneration temperature [18]. The hierarchical microstructure of Co/CZ@M/C, combined with high-efficiency filtration and low-temperature catalytic oxidation of soot particles, seems to have possible uses in the diesel particulate filter (DPF) field [19]. With a diesel oxidation catalyst (DOC), CO and HC are reduced drastically to zero, and NOx is reduced by 24.3% [20]. For the studies, a single-cylinder direct injection compression ignition engine that had been suitably modified to run in dual fuel mode with EGR was employed. The results of the trials showed that, at higher engine loads, the NOx-smoke emission trade-off was improved by the dual fuel mode with EGR without losing the characteristics of engine combustion and performance [21]. The main outcome of this study is that CO and HC emissions, two major issues for RCCI engines operating at part load, were reduced while NOx reduction increased with 8% EGR. Even though smoke emission is slightly greater with EGR than without EGR, it is still lower than in traditional mode (Diesel alone). Their work offered the novel idea that EGR can be utilized to lower the CO and HC emissions of RCCI engines operating at part load [22]. SCR technology should be developed for marine low-speed engines to meet the demands of high thermal efficiency, low pollutant emissions, and high sulphur fuel. Under the concomitant limitations of high sulphur fuel and low exhaust temperature, the low-speed diesel engine SCR systems will eventually give up some engine economy to obtain increased denitrification efficiency and operational reliability [23].

Based on the aforementioned literature review, it is clear that it is challenging to control the PM and NOx values in the environment. In this case, EGR lowers NOx, DPF collects PM, and SCR also lowers NOx emission. Therefore to control the PM and NOx, we have implemented the present framework with EGR combined with SCR & DPF to manage the emission.

3. Experimental setup and methodology

3.1. Modifications to an after-treatment process for engine

3.1.1. Engine with EGR system

Firstly, the EGR system was initially fitted to the diesel engine EGR gases, which also include water vapor, HC, CO, NOx, and CO_2, redirect some of the clean air entering the combustion chamber.

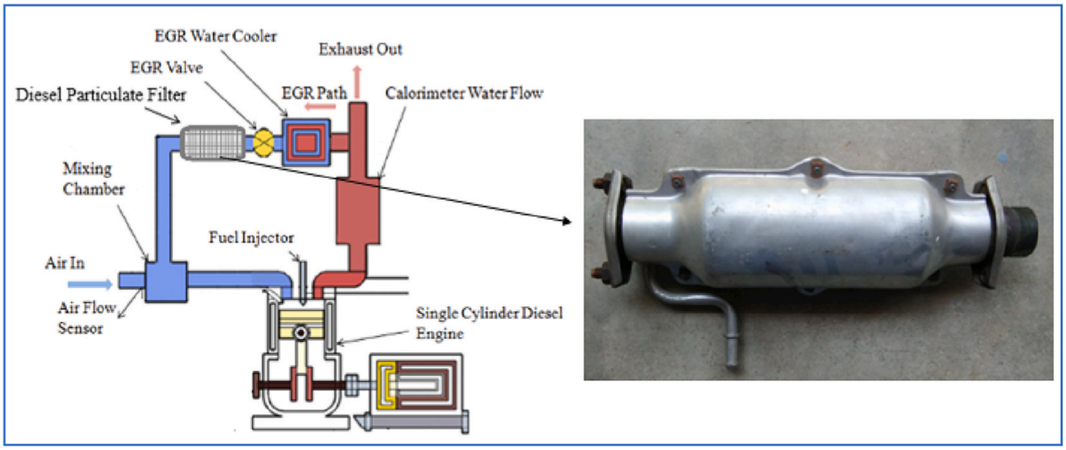

Fig. 1. Schematic diagram of EGR + DPF system.

The valve is typically used to control the rate at which EGR flows. The mixing chamber was utilized to ensure the correct mixing of exhaust and fresh air. The equation (i) is used to compute the EGR (%).

$$\text{EGR rate } (\%) = \frac{Q_{\text{without EGR}} - Q_{\text{with EGR}}}{\text{QwithoutEGR}} \text{ x } 100 \quad \text{(i)}$$

where $Q_{\text{without EGR}}$ is the airflow rate without EGR and it is equal to 26 kg/h and $Q_{\text{with EGR}}$ is 23.4 kg/h (10%), 20.8 kg/h (20%) and 18.2 kg/h (30) %. The dropdown of the airflow is 2.6 kg/h (10%), 5.2 kg/h (20%) & 7.8 kg/h (30%)

3.1.2. Engine with DPF + EGR system

Secondly, to capture the soot particles, the DPF system was installed. DPF has a wall thickness of 0.30 mm and a 200-CPSI construction. The installation of the EGR and DPF systems ensures that no PM is introduced into the combustion chamber during the recirculation of exhaust gases. It made use of the non-catalyzed cordierite wall-flow DPF. This Cordierite wall flow doesn't undergo any chemical reactions; it only traps the soot. Fig. 1 displays the schematic with EGR and DPF.

3.1.3. Engine with DPF + SCR system

Thirdly, the SCR system was set up as depicted in Fig. 2. The installation of the EGR and SCR systems results in the recirculation of exhaust gases being supplied to the combustion chamber together with CO_2, H_2O, and PM. A two-way catalytic converter, the SCR performs two jobs at once:

- Oxidation of CO to CO_2: $2CO + O_2 \rightarrow 2CO_2$
- Oxidation of HC (unburnt and partially burnt fuel) to $CO_2$and water: $C_xH_{2x}+2 + [(3x+1)/2]\ O_2 \rightarrow xCO_2 + (x+1)\ H_2O$ (a combustion reaction)

The schematic diagram with EGR and SCR is shown in Fig. 2.

Fig. 2 displays the schematic with EGR and SCR.

3.2. Diesel engine setup

In this study, a computerized TV1-Kirloskar diesel engine with a 3.5 kW output and a constant speed of 1500 rpm was used. An eddy current dynamometer is connected to the engine to regulate engine torque. The control panel regulates the load and engine speed. Table 1 provides information on the engine's specifications. NOx, HC, and CO are measured using an AVL gas analyzer.

3.3. Measuring devices

Table 2. Shows the ranges and accuracy of measuring devices. These measuring devices are used during the experimentation.

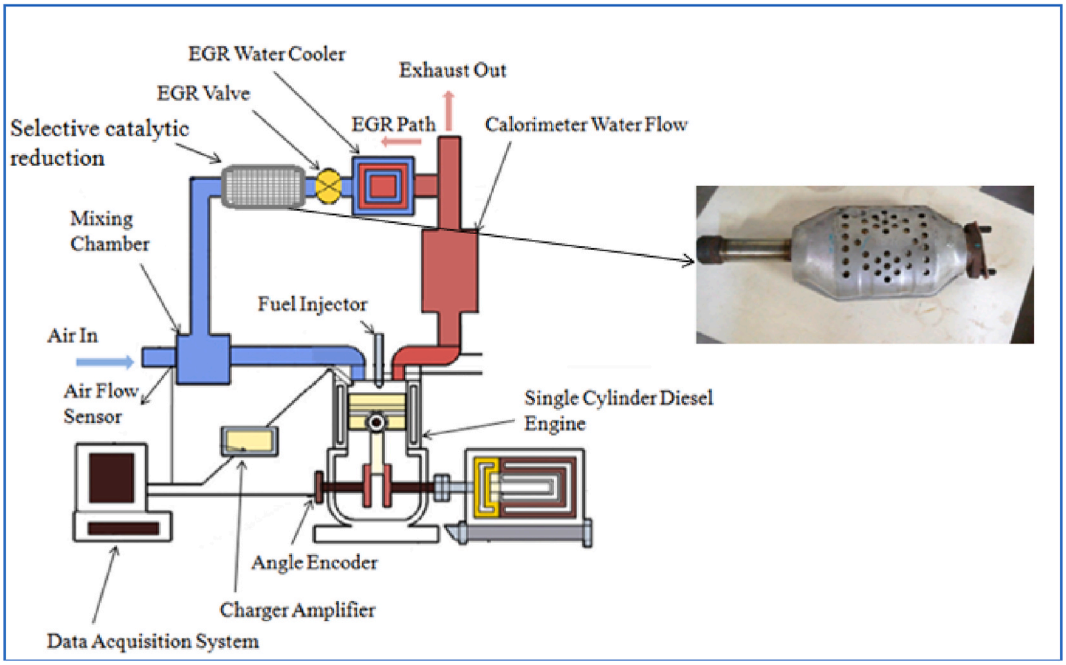

Fig. 2. Schematic diagram of EGR + SCR system.

Table 1
Information on diesel engine specifications.

Parameters	Details
Engine supplier	Apex Innovations Pvt. Ltd.
Engine type	TV1-KIRLOSKAR
Engine software	Internal combustion engine analyzer software (Version 9.0)
Loading type	An eddy current dynamometer model
No. of cylinder	1
No. of strokes	4
Rated power (kW)	3.5 at 1500 rpm
Timing of Injection (°CA. bTDC)	23
Swept volume (cc)	661
Stroke length (mm)	110
Cylinder bore (mm)	87.5
Compression ratio	17.5:1
Connecting rod length (mm)	234
Engine cooling type	Cooling water
Piston bowl	Hemispherical
Nozzle opening pressure (bar)	210

Table 2
Accuracy and ranges of measuring devices.

Quantity	Range	Accuracy
AVL gas analyzer	NO_x: 0–5000 ppm	±50 ppm
	CO: 0–10% by vol.	±0.03%
	HC: 0–20000 ppm	±10 ppm
AVL smoke meter	0–100%	±0.2%
Pressure Sensor	(0–110 bars)	±0.05 bar
Fuel flow sensor	0-5 psi	±0.1 psi
Crank angle encoder	0°–720°	±1°
Speed measuring	0–5000 rpm	±10 rpm
Air flow sensor	0–3.500 mm of H_2O	±1 mm of H_2O
Alternator	0–20 A, 0–450 V	±0.55 A, ± 1 V
Thermocouples	0–1000 °C	±1 °C

3.4. Experimental testing procedure

The baseline, EGR, EGR + DPF, and EGR + SCR are connected to the engine. The experimental work was done as explained above.

- The engine is connected to the battery. The water values are opened to circulate water for cooling the engine.
- The engine is started with no load applied to it and made to run at a constant rate of 1500 RPM. The engine is let to run so that it can be heated up and reach a steady state.
- The Exhaust Gas recirculation valve is opened to let only 10%, 20%, and 30% of the exhaust gas to be circulated. Caution is kept to keep the valve in that position throughout the experiment.

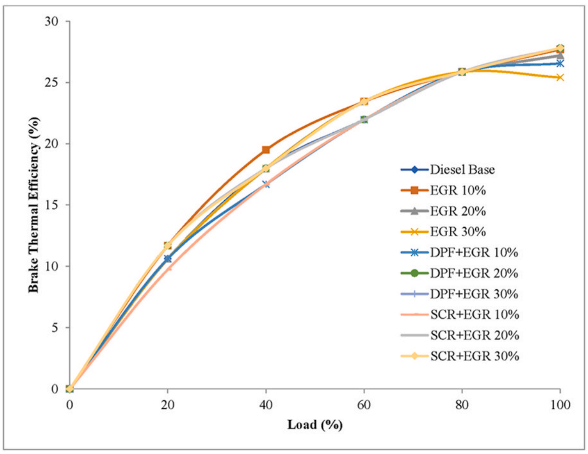

Fig. 3. Variation of BTE vs. Load.

- The fuel knob is turned towards the neutral position to let fuel flow to the burette. The amount of this fuel consumed in 1 min will be used to carry out the required measurements.
- The Emission analyzer is then connected to the secondary exhaust outlet, and the corresponding smoke readings are noted.
- The above steps are repeated thrice to reduce human error while taking readings.
- All the above steps are then repeated at 20%, 40%, 60%, 80% and Full load conditions. Caution is kept to keep the engine speed running at a constant rate of 1500 RPM.
- The above experiment will be conducted for conditions 20% EGR and 30% EGR.
- The above method is repeated same for the combination of EGR + DPF and EGR + SCR.

4. Results and discussion

Performance, combustion and emissions characteristics have been plotted from the data obtained based on the above procedure. Different comparisons are made in the graphs to decide the best possible combination.

4.1. Engine performance analysis

4.1.1. Brake thermal efficiency

The successful conversion of chemical energy present in fuel into heat energy and transformation into mechanical energy at the engine shaft is shown by brake thermal efficiency. With an increase in the load placed on the engine, BTE rises as shown in Fig. 3. BTE is mainly dependent on fuel heating value and fuel consumption. BTE for diesel as a fuel is 29.22 at 10% EGR at peak load. The other values of BTE at peak load are 27.28 at 20% EGR, and 25.41 at 30% EGR. We can therefore observe that BTE decreases with an increase in the EGR rate. Additionally, compared to lower EGR rates, the decrease in BTE at higher EGR rates is significant. This may be because the amount of fresh oxygen available for combustion decreases due to replacement by exhaust gases. The BTE of EGR + DPF is decreasing with further EGR rates level due to the back pressure that occurred in DPF. This is mainly due to the replacement of exhaust gases, which increases the soot levels and accumulate in DPF. Here, the soot particles are not vanishing in DPF because the temperature of the gases in DPF could not be able to generate more than 500 °C; due to this, the flow of the exhaust gases is not passing freely from the DPF system. In fact, the soot particles have the ability to get burn at 500 °C–600 °C. The combination of EGR + SCR is also performing poor performance due to the replacement of H_2O, CO_2, PM, and other gases; due to this, the combustion temperature is reducing and lowering the NOx levels.

4.1.2. Brake-specific fuel consumption

Fig. 4 shows the variation of BSFC with respect to the load. BSFC is decreased with an increment in load. This is an indication of the effective combustion of fuel. The BSFC is decreased by EGR 10% due to the return of unburned hydrocarbons. The further rise of EGR rates seems to increase in BSFC. When EGR and DPF are utilized together, the BSFC is increased because of the back pressure brought on by the soot deposit in the DPF. As the soot particles accumulate in the DPF, the flow of the exhaust gases falls flowing freely from the DPF, especially at low Load conditions because at low load conditions, the temperature of the exhaust will be low, and the trapped soot particles in DPF may not vanish. So, this is how it causes back pressure. Moreover, the flow rate of the fresh air from the atmosphere will reduce significantly as the EGR rate increases. The reintroduction of CO_2, water vapor, and PM into the combustion chamber develops incomplete combustion, which in turn increases the BSFC when EGR + SCR is used.

4.2. Engine combustion analysis

4.2.1. In-cylinder pressure

Fig. 5 shows the variation of In-cylinder pressure with the crank angle at full load conditions. Compared to the diesel baseline, the

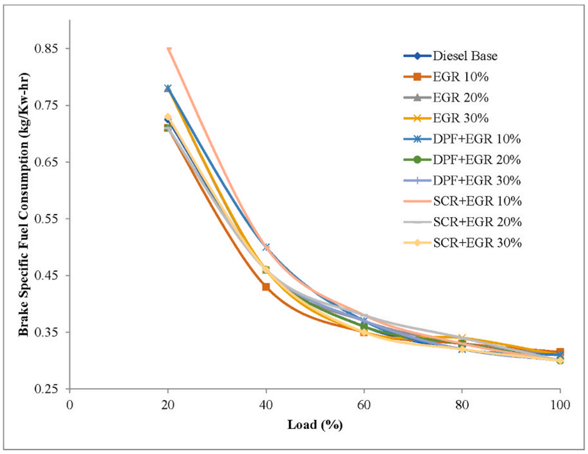

Fig. 4. Variation of BSFC vs Load.

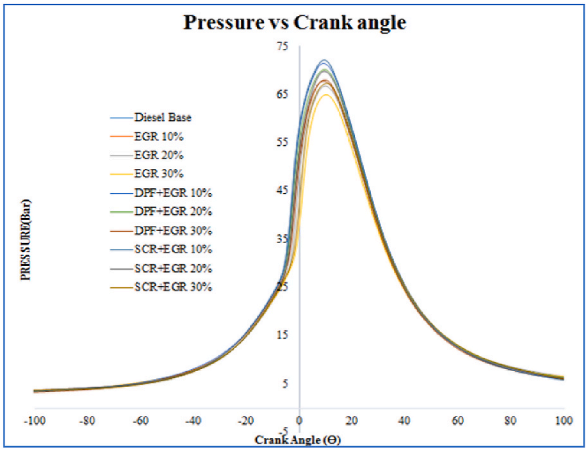

Fig. 5. In-cylinder pressure with the crank angle at the full load condition.

EGR application and with the EGR rate increase, the pressure rise is seen to be decreased. When compared to different EGR rates and their combinations with DPF and SCR, it is found that the 10% EGR rate with DPF and SCR combo performs best [24]. These drawbacks are observed to be due to the back pressure with DPF caused by and recirculating of H_2O, soot, and CO_2.

4.2.2. In-cylinder gas temperature

The variations of In-cylinder gas temperature concerning load are shown below in Fig. 6. The temperature is reduced by increasing the EGR rates. The reason for lowering the exhaust gas temperature is that the utilization rate of oxygen for combustion is relatively low and the specific heat of the intake air-fuel mixture is high. The temperature is slightly increased at higher load conditions for the combination of 10% EGR + DPF. The rest of the EGR rates with DPF are decreased in gas temperature. The maximum In-cylinder temperature is reduced for 10%, 20%, and 30% EGR with SCR; this is mainly due to the recirculating of exhaust gases which leads to incomplete combustion.

4.2.3. Heat release rate

Fig. 7 shows the variation of HRR with the crank angle at full load conditions. The late HRR is observed for 10%, 20%, and 30% EGR rates and shows a higher HRR due to the slow rate of combustion. The HRR for 10% EGR + DPF is observed to be early HRR and cannot attain a maximum HRR. For all EGR rates with the SCR combination, the early HRR is achieved and could not reach the maximum HRR. The HRR mainly relates to the Ignition delay and combustion process.

4.3. Engine emission analysis

4.3.1. Carbon Monoxide

Fig. 8 shows the CO change with load for various EGR rates and its DPF and SCR combo. Most of this CO is produced as a result of inadequate combustion. Components, including the fuel-air ratio, compression ratio, delay time, fuel type, and injection timing, all affect how CO develops. For each particular combination, the level of CO emissions is maximal at full load. However, it was observed that at 30% EGR + SCR, the CO generation increased considerably. It is primarily caused by incomplete combustion. CO increases with increasing EGR rates. The combinations of EGR + DPF are observed to be lower as compared to the other application of SCR and EGR.

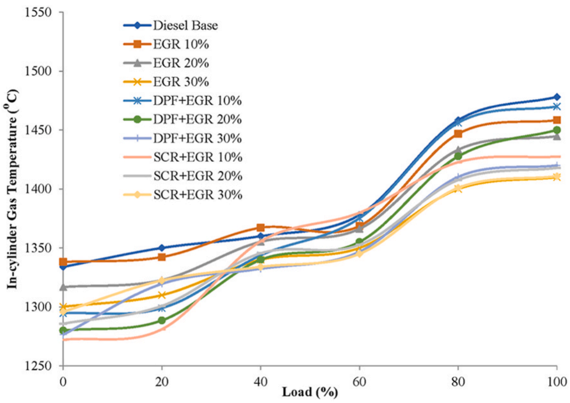

Fig. 6. In-cylinder gas temperature vs. Load.

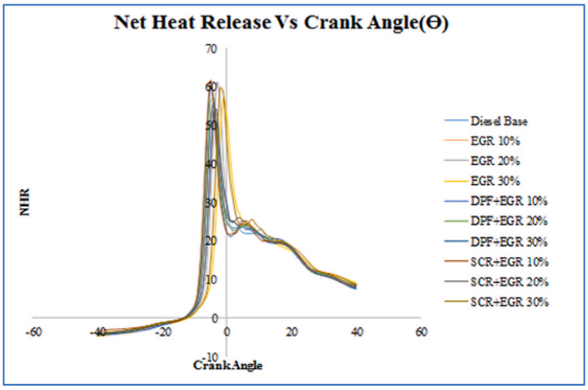

Fig. 7. Heat release rate with the crank angle at the full load condition.

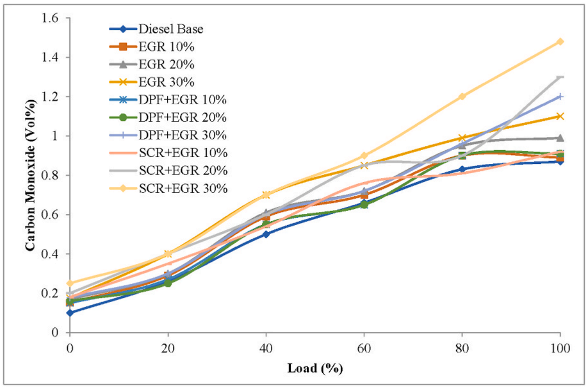

Fig. 8. Variation of Carbon monoxide vs. Load.

At higher EGR rates, CO emissions are increased due to the low availability of oxygen by EGR.

4.3.2. Hydrocarbon

As shown in Fig. 9, the HC emissions increase as the load increases. They are primarily formed as a result of insufficient fuel combustion and are fortified with a rich mixture. The temperature of the cylinder wall during mixture formation influences HC formation, particularly at the cylinder boundary. Furthermore, the fuel flowing into the combustion chamber is not involved in combustion along these lines, resulting in higher HC emissions for diesel, particularly at full engine load. It can be noted that the maximum amount of HC emission is at a full load of 30% EGR. The HC emission increases with EGR rates. Because there is less oxygen in the combustion chamber, the rich mixture results in incomplete combustion, which results in higher HC emissions in the exhaust. Because soot is accumulated in the DPF, the combination of EGR and DPF appears to be more effective in reducing HC emissions. The SCR, with a combination of EGR rates, appears to be ineffective in reducing HC emissions.

4.3.3. Oxides of nitrogen

Fig. 10 depicts the NOx variation for all tested systems as a function of the load on a compressed ignition engine. One of the most hazardous harmful exhaust pollutants from a diesel engine is NOx, which is sensitive to fuel quality, oxygen content, and combustion temperature. An increase in NOx was observed for the various systems as the load increased. Additionally, due to the buildup of carbon on the cylinder surface, burning chamber, and valve walls that serves as an insulator and raises the temperature in the engine cylinder, insufficient fuel ignition results in greater NOx outflow. In comparison to the other parameters, the NOx emission is highest at full load for 10% EGR. However, throughout all load operations, the application of EGR dramatically reduced NOx emissions. It can be seen that 30% EGR results in a greater reduction in NOx emissions. The graph of In-cylinder gas temperature demonstrates that the main cause of the decrease in NOx emissions is a lower combustion chamber temperature. The EGR + DPF is not so effective in reducing NOx compared to the other data. With the combination of SCR + EGR at different rates, the NOx levels are decreasing compared to all other parameters.

4.3.4. Smoke opacity

Fig. 11 depicts the variation in smoke opacity concerning load for all tested systems using a compressed ignition engine. One of the major toxic exhaust emissions from diesel engines is smoke opacity. The increase in load caused an increase in smoke opacity for the

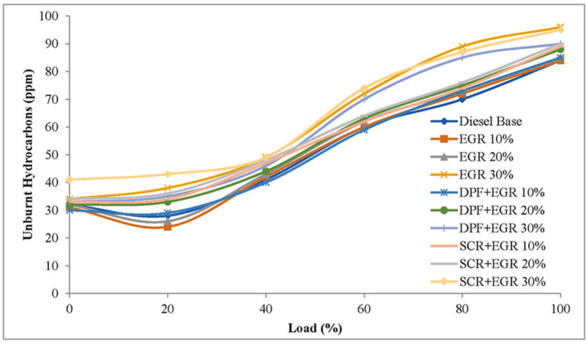

Fig. 9. Variation of Unburnt hydrocarbon vs. Load.

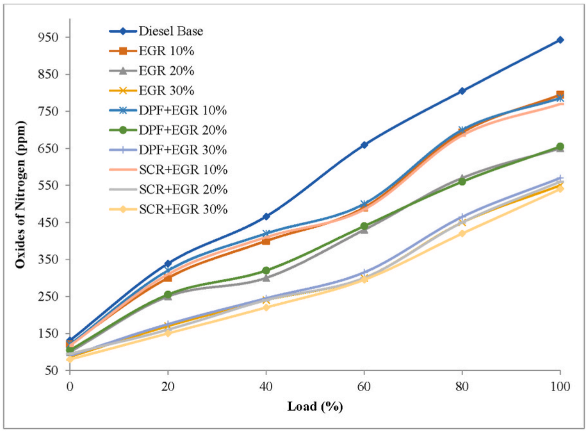

Fig. 10. Variation of Oxides of nitrogen vs. Load.

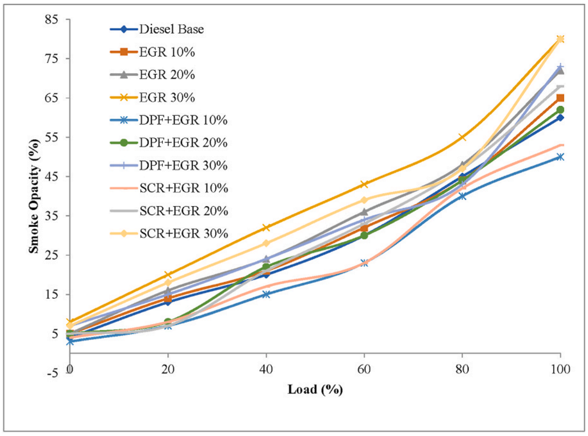

Fig. 11. Variation of Smoke Opacity vs. Load.

various systems. Furthermore, insufficient fuel ignition causes more smoke to escape due to incomplete combustion, which leads to the formation of soot particles at lower temperatures and higher load conditions. The soot particles are high at full load for increasing EGR rates. But by the use of DPF, the soot particles seem to decrease with EGR. The combination of DPF + SCR with EGR application soot particles is observed to be increased due to the recirculation of exhaust of H_2O and N_2. The SCR mainly covers the NO_X into H_2O and N_2. The DPF + SCR with 10% EGR application is having an appreciable reduction in emissions and without much affecting the performances.

5. Conclusions

Based on the obtained results from this study and by taking into consideration the first goal, which looks to reduce gas emissions, it is possible to mention that the outcomes of this work are: the brake thermal efficiency has a higher value when the EGR rate is 10% when compared to the other combinations, and fuel consumption is also reduced especially at partial load conditions.

As the rate of EGR increases the NOx level reduces but due to insufficient oxygen supply, the air-fuel ratio decreases hence reducing the brake thermal efficiency at higher loads. Here, as the EGR flow rate is increasing, the fresh air from the atmosphere flow rate is decreasing, and the mixture becomes a more lean mixture due to the lack of fresh air and more amount of fuel it is leading to a drop in the performance of the engine.

With the combination of EGR and DPF, the soot particle gets trapped hence allowing only the clean gases to pass through the EGR back into the combustion chamber. The level of HC and CO enters the combustion chamber, where they are completely burned, but because of the high temperature inside the combustion chamber, NOx levels also rise at the same time. Therefore, trapping the PM in the DPF and allowing the other gases in the combustion chamber has a positive effect at an EGR rate of 10%. In the DPF system, where the soot is trapped, higher EGR rates cause back pressure. Due to the soot buildup in the DFP, where the soot in the DPF cannot be eliminated at lower load circumstances because of the low temperature of the gases, the back pressure is continued.

With the combination of an SCR and EGR, the NOx levels get reduced due to the conversion of the NOx to nitrogen gas. But with the combination of an SCR and EGR the amount of CO_2 entering the combustion chamber also does increase, resulting incomplete combustion, which increases the value of HC and CO in the exhaust gases. The EGR 10% with SCR shows a good impact without damaging the performance of the engine.

The best possible combination depends on the performance of what gases are to be eliminated, keeping the EGR rate at an optimum value between 10% and 20%. If preference is given to reduce NOx, then we will combine 10–20% EGR with the SCR system, but if the preference is given to reduce HC, CO and soot, we need to utilize 10% - 20% EGR in combination with a DPF system which gives a little good impact in reducing the emissions. The implementation of the work can be utilizing the EGR system with the combination of DPF and SCR for reducing the Soot and NOx at low EGR rates only.

For further work, the combination of EGR + DPF + SCR may give appreciable results for controlling the Soot and NOx at a time.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Author statement

Megavath Vijay Kumar: Conceptualization, Software, Review, Editing, Writing, Original Draft, **Alur Veeresh Babu**: Conceptualization, Software, Review, Editing, Writing, Original Draft, **Ch. Rami Reddy**: Investigation, Formal Analysis, Supervision, Writing, **A. Pandian**: Conceptualization, Investigation, Supervision, Writing, **Mohit Bajaj**: Writing, Review, Editing, **Hossam M. Zawbaa**: Resources, Writing, Review, Editing, **Salah Kamel**: Supervision, Writing, Review, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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