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THE EFFECT OF EXHAUST GAS RECIRCULATION (EGR) IN COMPRESSION IGNITION ENGINE

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ABSTRACT

To meet stringent vehicular emission norms worldwide, various exhaust treatment techniques have been employed in modern engines. Oxides of nitrogen (NO_x) are formed during combustion inside cylinder which is responsible for major respiratory problems in human beings. NO_x also contributes to global warming and acid rain formation. One of the techniques of reducing the oxides of nitrogen in the exhaust from the engine is to use exhaust gas recirculation (EGR) technique. This paper presents a brief review on the effect of exhaust gas recirculation (EGR) on engine performances and exhaust emission characteristics of compression ignition engines based on the reports of different researchers available in the literature. The review shows that brake specific fuel consumption, brake thermal efficiency increases or decreases depending upon the operating conditions of the engine and EGR (exhaust gas recirculation) percentage in the diesel blends. Reduction in exhaust gas temperature, smoke density and NO_x were observed but emissions of hydrocarbon (HC), carbon monoxide (CO) and carbon di oxide (CO_2) are increased with the increase in EGR percentage without any engine modification.

Keywords: EGR, Diesel, BSFC, Efficiency, Emissions, Oxides of Nitrogen.

1. INTRODUCTION

The majority of the world's energy demand is met by fossil fuels. With the rapid development of the industry and society, the requirement of fossil fuels is growing higher and higher. Facing the challenges of limited fossil fuel reserves and stringent environmental constraints, the issue of finding substitutes for fossil fuels has become a major work for researchers studying internal combustion (IC) engines [1]. In the last two decades, the researchers and manufacturers have provided major reductions in the exhaust emission levels of the automobiles due to increasing global concern about the air pollution [2], but the problem has yet not been solved. So, from all aspects there is an urgent need to carry out research work to find out the renewable and green alternative fuels for meeting sustainable energy demand with minimum environmental impact. Over recent past years, stringent emission legislations have been imposed on NO_x, smoke and particulate emissions from automotive diesel engines worldwide. Diesel engines are typically characterized by low fuel consumption and very low CO emissions. However, the NO_x emissions from diesel engines still remain high. Hence, in order to meet the strict vehicular exhaust emission norms worldwide, several exhaust pre-treatment and post treatment techniques have been employed in modern engines. Exhaust Gas Recirculation (EGR) is a pre-treatment technique, which is being used widely to reduce and control the oxides of nitrogen (NO_x) emission from diesel engines. EGR controls the NO_x because it lowers oxygen concentration and flame temperature of the working fluid in the combustion chamber. However, the use of EGR leads to a trade-off in terms of soot emissions. Higher soot generated by EGR leads to long-term usage problems inside the engines such as higher carbon deposits, lubricating oil degradation and enhanced engine wear. Wagner et al. [3] tried to achieve lower emission of NO_x and soot using highly diluted intake mixture. At very high EGR rate (around 44%), emission of particulate matters decreased sharply with a continuous drop in NO_x emission but this high EGR rate significantly affect the fuel economy. Agarwal et al. [4] investigated the effect of EGR on performance and emissions, carbon deposits, and wear of various parts of a diesel engine and reported that thermal efficiency is increased and brake specific fuel consumption (BSFC) is decreased at lower loads with EGR compared to without EGR but at higher loads, thermal efficiency and BSFC are almost similar. Hydrocarbons, carbon monoxide, and smoke opacity are increased with EGR, but NO_x emission decreases drastically. Qi et al. [5] noticed that the brake specific fuel combustion (BSFC) and soot emission were slightly increased, and nitrogen oxide (NO_x) emission was evidently decreased with the increasing of EGR rate. But when the static injection timing retarded, BSFC was slightly increased, NO_x emission was significantly decreased. Brake thermal efficiency is increased to some extent and CO_2, CO and HC emissions were decreased with the supply of small amount of hydrogen without EGR but opposite trends are obtained with EGR in both cases as reported by Yadav et al. [6]. Based on the experimental work conducted by Anandavelu et al. [7] using diesel and eucalyptus oil fuel (EOF) blends without and with 15% EGR, it is reported that with the increase in percentage of eucalyptus oil in diesel, smoke, NO_x and unburned hydrocarbon emissions reduce.

2. EXHAUST GAS RECIRCULATION

Exhaust Gas Recirculation is an effective method for NO_x control. The exhaust gases mainly consist of carbon dioxide, nitrogen and water vapour. When a part of this exhaust gas is re-circulated to the cylinder, it acts as diluent to the combusting mixture. The specific heat of the EGR is much higher than fresh air; hence EGR increases the heat capacity (specific heat) of the intake charge, thus decreasing the temperature rise for the same heat release in the combustion chamber. Recirculated exhaust gas displaces fresh air entering the combustion chamber with carbon dioxide and water vapour present in engine exhaust. As a result of this air displacement, the amount of oxygen in the intake mixture is decreased. Reduced oxygen available for combustion lowers the effective air–fuel ratio which affects exhaust emissions substantially. In addition, mixing of exhaust gases with intake air increases specific heat of intake mixture, which results in the reduction of flame temperature. Thus combination of lower oxygen quantity in the intake air and reduced flame temperature reduces rate of NO_x formation reactions. The EGR (%) is defined as,

$$\%EGR = \frac{volume\ \ of\ \ EGR}{total\ intake\ charge\ into\ the\ cylinder} \times 100 \quad (1)$$

Another way of measurement of the extent of EGR is by the use of CO_2 concentration [15],

$$\text{EGR ratio} = \frac{[\text{CO}_2]_{\text{intake}} - [\text{CO}_2]_{\text{ambient}}}{[\text{CO}_2]_{\text{exhaust}} - [\text{CO}_2]_{\text{ambient}}} \quad (2)$$

Three popular explanations for the effect of EGR on NO_x reduction are increased ignition delay, increased heat capacity and dilution of the intake charge with inert gases. The heat capacity hypothesis states that the addition of the inert exhaust gas into the intake increases the heat capacity (specific heat) of the non-reacting matter present during the combustion. The increased heat capacity has the effect of lowering the peak combustion temperature. According to the dilution theory, the effect of EGR on NO_x is caused by increasing amounts of inert gases in the mixture, which reduces the adiabatic flame temperature [8].

It is difficult to employ EGR at high loads due to drop in diffusion combustion and this may result in an excessive increase in smoke and particulate emissions. But at low loads, unburnt hydrocarbons contained in the EGR re-burn in the mixture, leading to lower unburnt fuel in the exhaust. Apart from this, hot EGR would raise the intake charge temperature, thereby influencing combustion and exhaust emissions.

Implementation of EGR in diesel engines has problems like (a) increased soot emission, (b) introduction of particulate matter into the engine cylinders. When the engine components come into contact with high velocity soot particulates, particulate abrasion may occur. Sulphuric acid and condensed water in EGR also cause corrosion

3. EFFECT OF EGR ON PERFORMANCE

An alternative fuel/supplementary fuel are always evaluated on the basis of both engine performance and its environmental impacts. The effects of ethanol addition on different performance parameters have been discussed in this section.

3.1 Effect on Brake Specific Fuel Consumption and Brake Thermal Efficiency

Based on their experimental work, Agarwal et al.[4] reported that thermal efficiency is increased to some extent and brake specific fuel consumption (BSFC) is decreased at lower loads with EGR compared to without EGR. But at higher loads, thermal efficiency and BSFC are almost similar to that of without EGR. Yadav et al. [6] conducted an experiment to study the effect of EGR on a compression ignition engine in dual fuel mode (hydrogen-diesel) and observed that brake thermal efficiency was increased slightly with hydrogen enrichment without EGR but it decreases at high rate of hydrogen with EGR whereas brake specific fuel consumption (BSFC) without EGR was less compared to that of with EGR in presence of hydrogen. On the other hand, due to better mixing of hydrogen with air, BSFC with hydrogen enrichment and without EGR was less compared to that of neat diesel operation. It is experimentally observed by Anandavelu et al. [7] that the brake thermal efficiency is improved for all EOF blends compared with diesel operations without and with 15% EGR. And also due to the chemical effect, reburning of HC enters the combustion chamber with the recirculated exhaust gases and causes the dissociation of carbon dioxide which is also attributed to this improvement in efficiency. Kim et al. [11] carried out an experiment on a diesel engine to study the effect of EGR and found that specific fuel consumption is increased by 2 to 3 % with EGR rate. Qi et al. [5] experimentally investigated the effect of EGR rate on the combustion and emissions of a diesel engine and noticed that the brake specific fuel combustion (BSFC) was slightly increased with the increasing of EGR rate. Similar trend was observed in case of brake specific fuel consumption by Fang et al. [10] in their experimental study on a homogeneous charge compression ignition engine. As a case study, experimental results from the works of Yadav et al. [6] and Anandavelu et al. [7] have been presented in graphical form in figure 1 and figure 2 respectively. From the graphs, it is observed that brake specific fuel consumption is increased with EGR in presence of hydrogen and brake thermal efficiency is increased with the increase in percentage of eucalyptus oil in EOF and diesel blend.

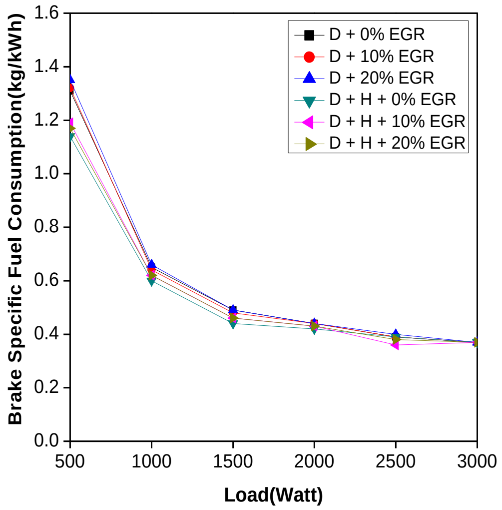

Figure 1: Variation of Brake Specific Fuel Consumption vs Load [6]

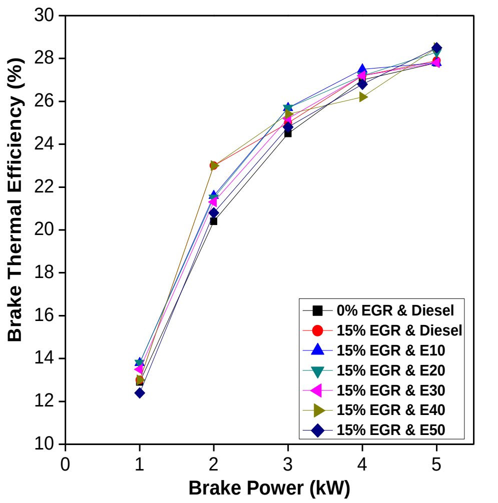

Figure 2: Variation of Brake Thermal Efficiency vs Brake Power [7]

3.2 Effect on Exhaust Gas Temperature

Agarwal *et al.* [4] investigated the effect of EGR on performance and emissions of a diesel engine and observed that exhaust gas temperature is increased with increase in load without EGR and is higher than temperature of exhaust gas with EGR. But exhaust gas temperature is decreased with increase in EGR rate due to lower concentration of oxygen in combustion chamber and higher specific heat of intake air mixture. Also the same trend was observed by Yadav *et al.* [6]. As a case study, experimental results from the works of Agarwal *et al.* [4] have been presented here in graphical form in figure 3. From the graph, it is observed that exhaust gas temperature decreases with increase in EGR rate.

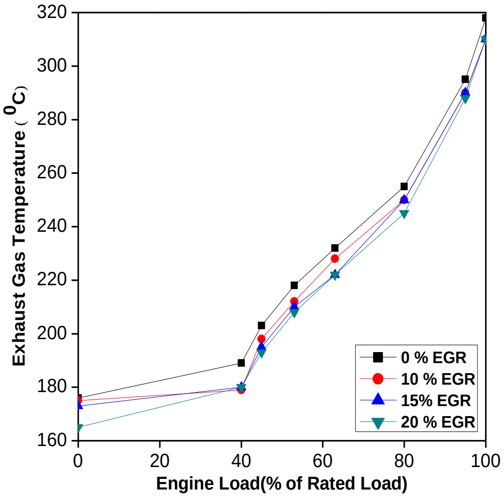

Figure 3: Variation of Exhaust gas Temperature vs Load [4]

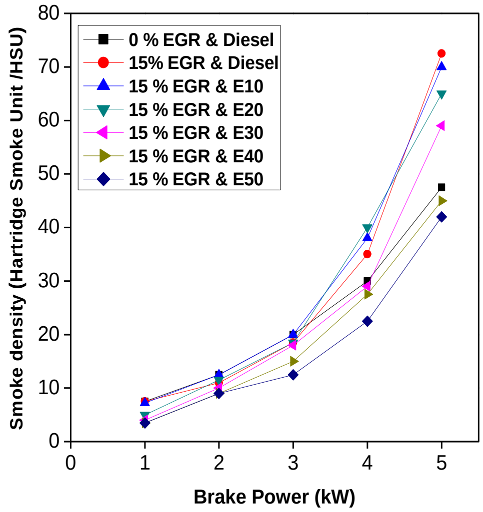

Figure 4: Variation of Smoke Density vs Brake Power [7]

4. EFFECT OF EGR ON EMISSIONS

Exhaust emissions like HC, CO, CO_2, NO_x, smoke opacity which have been evaluated by different researchers are reported in this section.

4.1 Effect on Smoke emission

It is reported by Anandavelu et al. [7] that emission for EOF (diesel fuel and eucalyptus oil) blends result in a slightly lesser smoke emission than diesel fuel with and without EGR. It is revealed that for higher concentration of eucalyptus oil in blend, the smoke emission is reduced. This trend may be attributed to the good mixture formation of EOF blends, and the oxygen present in the blend leads to an improvement in diffusive combustion. The opposite trend was observed by Agarwal et al. [4]. From their experimental study on a homogeneous charge compression ignition engine

Fang et al. [10] reported that smoke opacity increases with low level of EGR than that of without EGR. As a case study, experimental results from the works of Anandavelu et al. [7] have been presented here in graphical form in figure 4.

4.2 Effect on CO emission

Hu *et al.* [9] studied the brake specific CO concentration versus EGR rate at different hydrogen fractions. From the experiment shows that CO emissions show little variation or slight decreasing trend with the increase of EGR rate. Although CO in ppm may increase with the increase of EGR as oxygen concentration is decreased and post-flame oxidation is decreased, the engine power output will also decrease with the increase of EGR rate. The CO gives a slight decreasing trend with the increase of EGR rate. CO shows an increasing at high EGR rate and this would be due to the fast increase of CO at high EGR rate. CO maintains the low value in the case of EGR introduction. Yadav and Sharma [6] observed that at 80% load CO emission for neat diesel operation was lesser than using EGR. In case of hydrogen enrichment without EGR, CO emission was 0.18% by volume. In case of EGR, CO emission increased due to oxygen deficient operation while increase of EGR rate, reaction speed and in-cylinder temperature were decreased simultaneously more exhaust gas reduces the O_2 concentration. Based on their experimental investigation on a homogeneous charge compression ignition (HCCI) engine Fang *et al.* [10] reported that Co emission is increased with the rise of pilot quantity due to incomplete combustion. From their experimental study on a HCCI engine, Xingcai *et al.* [12] observed that CO emission was increased with increase of EGR rate up to 35%.S

The same findings were observed by Agarwal *et al.* [4] and Gu *et al.* [14].

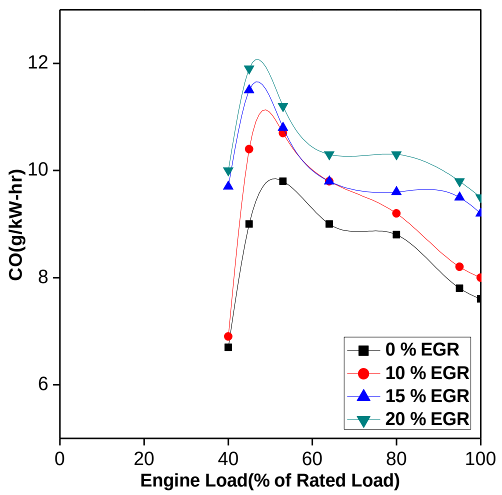

Figure 5: Variation of CO vs load [4]

The experimental study by Agarwal *et al.* [4] is graphically represented in figure 5. From the graph, it is observed that CO emissions increase with increasing EGR.

4.3 Effect on NO_x emission

It is experimentally observed by Anandavelu *et al.* [7] that, a reduction of about 50–60% NO_x is found in the EGR engine for EOF (diesel fuel and eucalyptus oil) blends compared to standard diesel fuel operated in the engine without EGR and NO_x emission was 682 ppm and 281 ppm for the engine operated without EGR and with 15% EGR for diesel fuel. Yadav and Sharma [6] also observed the same trend. The reason for this higher concentration of NO_x in case of hydrogen enrichment without EGR was peak combustion temperature and high residence time of the high temperature gases in the cylinder. Hu *et al.* [9] studied EGR rate at different hydrogen fractions. For both natural gas combustion and natural gas–hydrogen combustion, NO_x concentration decreases with the increase of EGR rate. Mixture dilution due to EGR introduction and this reduces the combustion temperature. While introducing to EGR, decrease the amount of heat release and the combustion temperature. Large specific heat capacity gases like CO_2 and H_2O, which absorbs part of released heat and decreases the combustion temperature. If the combustion temperature reduces than the formation of NO_x is decreased. Agarwal *et al.* [4] observed the main advantage of EGR in reducing NO_x emissions from diesel engine. The reduction in NO_x at higher loads is higher due to reduced oxygen concentration and decreased flame temperatures in the combustible mixture.

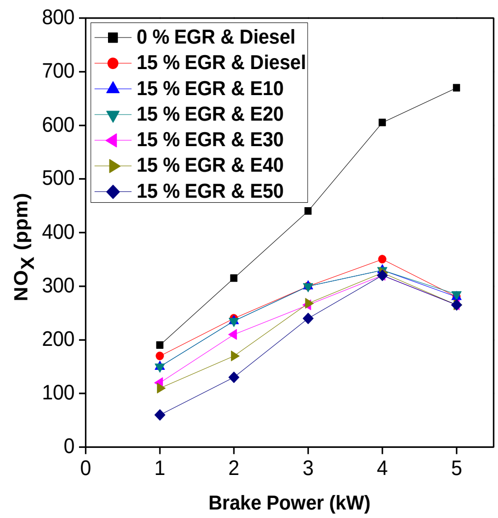

Figure 6: Variation of NO_x vs Brake Power [7]

It was observed by Fang *et al.* [10] that NO_x emission decreased with increase in pilot quantity up to a certain level and then it increases slightly. They also observed that NO_x emission was reduced markedly low level of EGR (15% and 25% EGR) when compared with no EGR. Similar result was obtained by Xingcai *et al.* [12] from their experimental study on a homogeneous charge compression ignition engine. When the intake and exhaust oxygen concentrations decreased with increased EGR rate, emission of soot increased resulting in decrease of NO_x emissions as reported by Kim *et al.* [11]. NO_x formation is reduced up to 89% with EGR was obtained by Cha *et al.* [13] from their study. The experimental study by Anandavelu *et al.* [7] is graphically represented in figure 6. From the graph, it is observed that NO_x emission was reduced by almost 50% for all EOF (diesel fuel and eucalyptus oil) blends such as E10 (10% eucalyptus oil and 90% diesel fuel), E20 (20% eucalyptus oil and 80% diesel fuel) etc. than diesel operations without and with 15% EGR.

4.4 Effect on CO_2 emission

Yadav and Sharma [6] observed that at 80% load CO_2 emission for hydrogen enrichment without EGR was 3.6% by volume whereas that for neat diesel was 4% by volume. Due to the use of EGR, CO_2 emission increased with the increase in EGR percentage. At 80% load CO_2 emission for 10% EGR was 3.8% by volume and that of 20% EGR was 3.9% by volume. The reason of this increase in CO_2 emissions in case of EGR was the presence of CO_2 in exhaust gas. Hu *et al.* [9] studied that the brake specific CO_2 concentration versus EGR rate at various hydrogen in the case of small EGR rate, CO_2 emissions show little variation or slight decrease with the increase of EGR rate. CO_2 shows an increasing trend at large EGR rate and this would be due to the CO_2 increase from EGR and decreasing in power output at large EGR rate. As a case study, experimental results from the works of Yadav *et al.* [6] have been presented here in graphical form in figure 7. From the graph, it is observed that the CO_2 emission was decreased for enrichment of hydrogen without EGR compared to neat diesel operation due to absence of carbon in hydrogen molecule.

4.5 Effect on HC emission

Anandavelu *et al.* [7] observed a slight increase in HC emissions emission with diesel fuel in EGR compared to without EGR engine. The UBHC emission is 38 and 47 ppm for diesel without and with EGR, respectively. All EOF blends in EGR engine results in lesser UBHC emission. This is probably because the oxygen content in EOF blends compensates the oxygen deficiency and leads to complete combustion. Unburned hydrocarbon (UBHC) emission decreased by 5% for hydrogen enrichment without EGR compared to neat diesel operation due to the absence of carbon in hydrogen as reported by Yadav *et al.* [6].When rate of EGR increases, HC emission increased due to lower excess oxygen available for combustion which results in incomplete combustion but level of emission was little compared to neat diesel operation. Hu *et al.* [3] studied similar trend at different hydrogen fractions. HC shows little variation at low EGR rate and HC shows a remarkable increase when EGR rate is over a certain value the increasing of HC emissions with the increase of EGR rate can be explained as the following reasons. With the increase of EGR rate, the in-cylinder gas temperature and wall temperature are decreased, and this leads to HC formation from the wall quenching layer. Burning velocity is decreased with increasing EGR rate, and this increases the combustion duration and at high EGR rate may leads to mixture bulk quenching and remarkable increase in HC. Xingcai *et al.* [12] from their experimental study reported that with the increase in EGR rate (up to 35%), hydrocarbon (HC) emission increased. From their experimental study, Gu et al. [14] observed that with the increase in EGR rate, cylinder gas temperature decreases which decreases HC oxidation resulting in lower HC emission. As a case study, experimental results from the works of Yadav *et al.* [6] have been presented here in graphical form in figure 8. From the graph, it is observed that the UBHC emission was decreased for enrichment of hydrogen without EGR compared to neat diesel operation.

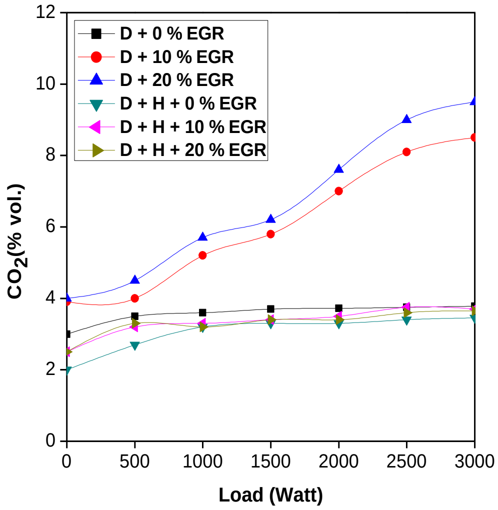

Figure 7: Variation of CO_2 vs Load [6]

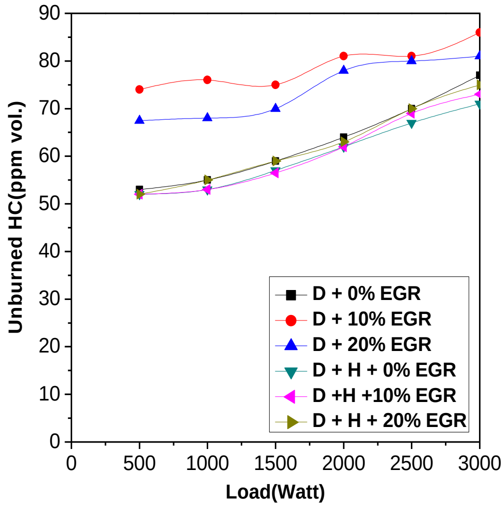

Figure 8: Variation of Unburned Hydrocarbon vs load [6]

5. CONCLUSIONS

From the above study, it can be concluded that EGR is a very useful technique for reducing the NO_x emission of CI engine. The brake specific fuel consumption is increased with EGR in presence of hydrogen and the brake thermal efficiency is increased with the increase in percentage of eucalyptus oil in EOF-diesel blend due to higher intake charge temperature and higher calorific value of eucalyptus oil fuel (EOF). Also for pure diesel fuel the brake thermal efficiency is decreased as the specific fuel consumption increases with EGR condition. From the emission point of view, it is observed that with the increase in percentage of the eucalyptus oil in diesel, the smoke emission is reduced whereas HC and CO emissions increase with increasing EGR. Also the same trend is observed for pure diesel fuel. About 50–60% reduction in NO_x emission is marked at all loads for all EOF blends compared with diesel operations without and with 15% EGR.

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