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TECHNICAL PAPER

Effects of EGR rate on performance and emissions of a diesel power generator fueled by B7

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Abstract This paper analyses the impacts of the application of an exhaust gas recirculation (EGR) system on the performance and emissions of a stationary, direct-injection diesel engine operating with diesel oil containing 7% biodiesel (B7). Experiments were carried out in a 49-kW diesel power generator with the adapted EGR system, and engine performance and emissions were evaluated for different load and EGR settings. The results were compared with the engine operating with its original configuration without the EGR system, and revealed a reduction of peak cylinder pressure and fuel conversion efficiency, mainly at high engine loads. The use of EGR caused opposite effects on carbon dioxide (CO_2), carbon monoxide (CO) and total hydrocarbons (THC) emissions, depending on load and EGR rate, showing an increase in most situations. The application of EGR consistently reduced oxides of nitrogen (NO_X) emissions, reaching a maximum reduction close to 30%. In general, the use of EGR increased CO_2, CO and THC emissions at high loads. The use of 7.5% EGR was found to be at an adequate rate to simultaneously reduce CO, THC and NO_X emissions at low and moderate loads, without major penalties on CO_2 emissions and engine performance.

Keywords Diesel engine · Exhaust gas recirculation · Emissions · Fuel conversion efficiency · Power generation

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1 Introduction

The emissions produced by diesel engines have a serious impact on both the environment and human health. Significant amounts of oxides of nitrogen (NO_X) are generated, which is a serious cause of smog, ground-level ozone, acid rain and also human diseases, such as asthma, coughing, or nausea [1]. Exhaust gas recirculation (EGR), which returns a portion of the engine exhaust gas to the combustion chamber via the intake system, shows a great potential to reduce NO_X emissions [2, 3]. The application of this technique to spark ignition and compression ignition engines has been studied with regard to its effects on engine performance, inlet air temperature control, combustion control and dual-fuel operation [4–12]. The possibility of reducing NO_x emissions with the use of EGR rate results from thermal, chemical and dilution effects [8, 9, 13–16]. In the thermal effect, the high specific heat of exhaust carbon dioxide (CO_2) and water (H_2O), compared to oxygen (O_2) and nitrogen (N_2) in the intake air, reduces combustion temperature. In the dilution effect, the reduction of oxygen mass fraction due to the displacement of some of the oxygen in the fresh intake air charge by inert gases causes a reduction in the local flame temperature because of the spatial broadening of the flame. In the chemical effect, recirculated H_2O and CO_2 are dissociated during combustion by an endothermic process, reducing flame temperature and modifying the NO_X formation process.

Ladommatos et al. [17–20] presented a series of works focused on understanding the influence of EGR on combustion and emissions in a four-cylinder diesel engine. To simulate the different effects of EGR, the authors added synthetic gases in the engine intake manifold. Air dilution reduced in-cylinder peak pressure, heat release rate and temperature. Reduced availability of O_2 decreased ignition delay, NO_X and NO, but increased unburned hydrocarbons (THC), soot, and particulate matter (PM) emissions. The studies highlight that NO_X reduction is mostly due to the dilution effect, with a small contribution of the chemical effect, and a negligible contribution of the thermal effect.

Zheng et al. [21] also added synthetic gases to the engine intake air to reproduce the essential characteristics of EGR without the influence of temperature, pressure, gas concentration and transient effects of a real system. The results showed that increasing CO_2 concentration reduces in-cylinder pressure and temperature during the compression stroke. The authors emphasize that EGR systems reduce NO_X emissions, but may increase exhaust PM emissions, sulfur salts and other abrasive and corrosive substances that cause piston and cylinder wear.

The use of EGR is limited by increased PM emissions and reduced engine thermal efficiency, which causes a NO_X/PM trade-off [9, 14–16, 22–24]. He et al. [8] explain that the use of high EGR rates is possible with the delay of diesel injection, reducing engine efficiency losses, but with increasing soot emissions. The optimized EGR rate for THC, CO and NO_X emissions is between 5 and 15%. Hussain et al. [24] also observed that 15% EGR rate is effective in reducing NO_X emission substantially without deteriorating engine performance in terms of fuel conversion efficiency, brake specific fuel consumption, and emissions. The low oxygen level at high EGR rates causes incomplete soot oxidation [25] and leads to long-term problems, such as carbon deposits and lubricating oil degradation [26]. To overcome this conflict, low-temperature combustion techniques (LTC) may be employed [27]. These techniques aim to separate the event of diesel injection from combustion, to reduce NO_X and soot emissions simultaneously. For the same EGR rate, the use of an oxygenated fuel, such as biodiesel, can simultaneously reduce THC, CO and smoke emissions, compared to diesel oil [1].

The use of EGR in transient state is a challenge due to fluctuations in the recirculation system, which can cause peaks of NO_X and soot emissions [28]. Schubiger et al. [29] showed that the use of EGR in a diesel engine increased the premixed phase of combustion. Peak heat release rate was reduced at high loads and increased at low loads. Ignition delay and combustion duration were also increased. A EGR rate of 40% achieved extremely low levels of NO_X emissions, but with increased emissions of PM, specific fuel consumption and engine noise levels.

Hussain et al. [24] and Agarwal et al. [30] noticed that diesel engines tolerate high EGR rates at low loads, since there is high oxygen concentration in these conditions, compared to high loads. With increasing load, inert gases are predominant in the exhaust, causing increased soot emissions due to reduced availability of oxygen. With EGR rates up to 20% a slight increase of fuel conversion efficiency at low loads was observed, explained by re-burning of hydrocarbons that enter the combustion chamber with the recirculated exhaust gas [30]. The authors reported reduced exhaust gas temperature, increased intake charge temperature and reduced fuel conversion efficiency with increasing EGR rate. EGR increased exhaust CO and THC emissions, and gas opacity, due to the dilution effect, and reduced NO_X emissions, due to reduced flame temperature. A direct-injection diesel engine operating at constant speed with up to 30% of EGR rate achieved a reduction of up to 30% of NO_X emissions, decreased exhaust gas temperature and increased ignition delay, opacity and CO emissions [31].

Selim et al. [32] and Niemi et al. [33] investigated the effects of using EGR cooling systems. The use of hot EGR increases in-cylinder pressure, which can decrease thermal efficiency losses due to a faster combustion, but cold EGR achieves lower NO_X levels [32]. In comparison with hot EGR, the specific fuel consumption with cold EGR is higher for EGR rates up to 10%, and lower with higher EGR rates [33]. Maiboom et al. [13] showed that, at constant EGR rate, the temperature of the recirculated exhaust gas causes different effects on engine performance. These effects depend on operating conditions, with positive and negative aspects using hot or cold EGR.

Wei et al. [34] stated that an engine with hot EGR can use the high exhaust gas temperature to heat the intake charge, thus improving combustion and fuel conversion efficiency, while the cooled EGR increases intake density and, thereby, engine volumetric efficiency. Whilst the decreased temperature of cold EGR can further reduce NO_X emissions, THC emissions and cycle-by-cycle variations are increased compared with those of hot EGR. The difficulties of using EGR cooling systems are the deposits of THC, PM and soot inside the system, which produce fouling and cause degradation in the heat transfer performance [35, 36].

This work analyses the combustion characteristics, performance and emissions of a 49-kW stationary diesel engine operating with diesel fuel containing 7% biodiesel (B7), for different EGR rates and loads applied. The objective is to verify if the adaptation of an EGR system to an engine not originally conceived with this technology can satisfactorily reduce NO_X without deteriorating engine performance or increasing other emissions (CO_2, CO and THC). Furthermore, it aims to give an insight if the use of a fuel blend containing an oxygenated biofuel can counterbalance the reduced oxygen availability in the gas when using EGR. The choice of B7 is justified by the Brazilian government law No. 13033/2014, which established the compulsory addition of biodiesel to diesel oil to 7% from 1 November 2014 [37]. With the use of the biofuel blend, it is expected that CO and THC can be adequately oxidized, thus avoiding significant increase of emissions of these components. Currently, there are no national regulations of gas emissions for diesel power generators in Brazil. To reduce the emissions in the city of São Paulo, the municipal government ruled that changes must be made to reduce the emissions of these equipments [38]. The use of EGR systems is an alternative to reduce NO_X emissions from diesel power generators with simple mechanical modifications.

2 Methodology

2.1 Experimental setup

Experiments were carried out in a diesel power generator equipped with a naturally aspirated, four-stroke, four-cylinder diesel engine. Table 1 shows the main engine characteristics. The fuel was directly injected in the combustion chamber by a mechanically controlled system, and the fuel injection settings were not changed during the experiments.

For recirculation of the exhaust gas, an appropriate pipeline was installed with no insulation, therefore allowing the recirculated gas to partially cool down by natural convection external to the pipe. The EGR quantity was regulated by an electric valve installed in the EGR loop. An electronic system was developed to control the valve position and the EGR rate (%). The EGR rate is defined as the mass percent of the recirculated exhaust gas (M_{EGR}) in the total intake mixture (M_{in}). Several authors report in their works [13, 14, 21, 24] that the EGR percentage can also be calculated as the recirculated CO_2 fraction. The fresh intake air contains negligible amounts of CO_2, while the recycled portion carries a substantial amount of CO_2 produced from combustion that increases with EGR flow rate and engine load. Thus, comparing the CO_2 concentrations in the engine exhaust (CO_{2_exh}) and intake (CO_{2_EGR}) is a practical way to determine EGR rate. Two taps were built in the intake and exhaust manifolds to sample the gas and measure CO_2 concentration, for calculation of the EGR rates according to:

$$\text{EGR}\ (\%) = \frac{(CO_{2\_EGR} - CO_{2\_atm})}{(CO_{2\_exh} - CO_{2\_atm})}. \quad (1)$$

Table 1 Diesel engine specifications

Parameter	Type or value
Model	MWM D229-4
No. of cylinders	4
No. of strokes	4
Type of injection	Direct
Bore × stroke	102 mm × 120 mm
Total displacement	3.922 L
Firing order	1-3-4-2
Maximum power at 1800 rpm	44 kW
Aspiration	Natural
Compression ratio	17:1
Coolant	Water

A data acquisition system was used to assess engine performance. The system consists of sensors, transducers, signal conditioning circuits, two data acquisition boards and a program developed in LabVIEW platform. A schematic drawing of the experimental apparatus is shown by Fig. 1. The intake air mass flow rate was measured by an orifice plate with uncertainty of ±2.3 kg/h. Fuel consumption was measured by a platform balance with uncertainty of ±0.1 kg/h. K-type thermocouples were used to measure temperature in several locations, including fuel tank, ambient air, inlet air, orifice plate inlet, and exhaust gas, with uncertainty of ±2 °C. Cooling water temperature was measured by a PT-100 sensor, also with uncertainty of ±2 °C. The inlet air humidity was determined by a thermo-hygrometer with uncertainty of ±2.5% of reading, and ambient pressure was monitored by a Torricelli barometer with resolution of ±1.3 kPa.

The engine load was measured by an electric transducer with uncertainty of ±1%. The in-cylinder pressure was measured by a piezoelectric pressure transducer with resolution of ±0.5%. Total HC emissions were analysed by a heated flame ionization detector (HFID) with resolution of ±1 ppm. NO_X emissions were analysed by a heated chemiluminescent analyser (HCLD) with resolution of ±1 ppm. CO and CO_2 emissions were measured by non-dispersive infrared (NDIR) analysers with resolution of ±1 ppm and ±0.01%, respectively.

2.2 Experimental procedure

The fuel used was a commercial N. 2 diesel oil containing 7% of biodiesel, whose values of density, viscosity and water content are shown in Table 2. The engine load was varied from 0 to 30 kW in intervals of 5 kW at the constant engine speed of 1800 rev/min. This speed was chosen because it provides an output power frequency of 60 Hz, which is the standard value of Brazilian electric power

Fig. 1 Schematics of the experimental apparatus

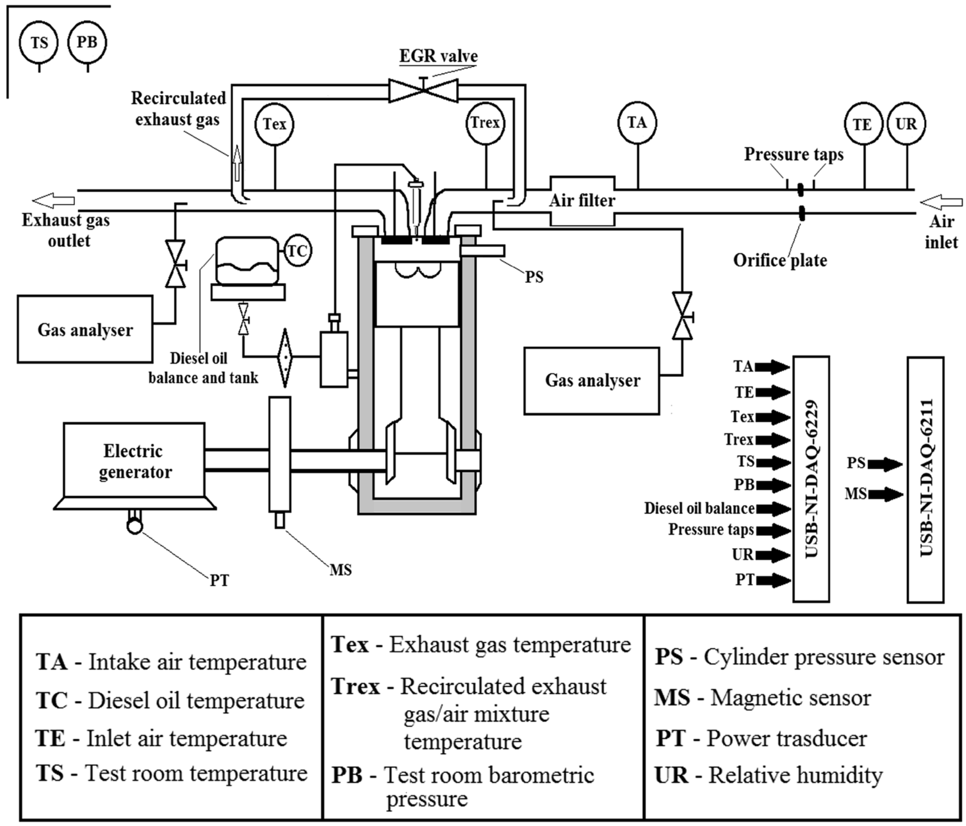

Table 2 Properties of diesel oil–ethanol blends

Property	Value	Method
Density at 20 °C (kg/m^3)	842 ± 1	ASTM D4052
Viscosity at 40 °C (mm^3/s)	3.0 ± 0.1	ASTM D7042
Water content (mg/kg)	103 ± 2	ASTM E203

Table 3 Total uncertainty of the measured parameters

Parameter	Uncertainty
Load power	0.02 kW
Specific fuel consumption	0.02 g/kW h
CO_2 emissions	6.00 g/kW h
CO emissions	0.21 g/kW h
THC emissions	0.18 g/kW h
NO_X emissions	0.05 g/kW h

grid. The ISO 3046-1:2002 standard was used to correct the load power and fuel consumption to standard conditions. The engine was operated with and without EGR, and the results compared. The EGR rates used were 0% (EGR0), 2.5% (EGR2.5), 5.0% (EGR5), 7.5% (EGR7.5) and 10.0% (EGR10).

The experiments were performed under steady-state conditions, after the exhaust gas temperature and the cooling water temperature were stabilized. In each test, a fixed load was applied during 10 min, which included the stabilization period followed by data measurement and acquisition at steady state. Depending on the load applied, the stabilization period was 2–5 min; therefore, the period of data acquisition in a single test at fixed load corresponded to a minimum of 4500 engine cycles. The results shown in the following section represent the average of three tests at each load, varying the engine load from 0 to 30 kW. The uncertainties of the measurements were calculated following the methodology by Kline and McClintock [39].

3 Results and discussion

The engine was operated at 1800 rpm with different loads and EGR rates (from 0 to 10%) to investigate the effect of EGR on engine performance and emissions. The performance and emission data were analysed and presented graphically for gas pressure inside the cylinder, heat release rate, air mass flow rate, thermal efficiency, CO_2, CO, THC and NO_X-specific emissions. The uncertainties of the measurements are presented in Table 3.

The in-cylinder pressure and the corresponding heat release rate at the load of 25 kW are shown in Figs. 2 and 3, respectively. The peak pressures are slightly decreased for all the EGR rates, by about 2%, in comparison with operation with no EGR (Fig. 2), in accordance with Refs. [4, 6, 21, 22, 25]. The use of EGR increases the intake charge specific heat capacity and reduces O_2 availability, which has a negative effect on the combustion rate and leads to reduced values of peak cylinder. Moreover, the dissociation of H_2O and CO_2 reduces the flame temperature, due to an endothermic process, leading to a reduction in NO_X formation. As a consequence of decreased combustion temperature, the peak heat release rate is also reduced with the use of EGR (Fig. 3). The higher reductions of the peak heat release rate were observed for operation with 7.5 and 10% EGR. The biodiesel effects have not been investigated here, but, according to the literature, its presence in the diesel fuel may have caused a slight reduction in the in-cylinder peak pressure and peak heat release, especially at full load, mainly due to poor atomization and inadequate air–fuel mixing of biodiesel blends [40, 41].

Figure 4 shows the intake air mass flow rate for operation with different EGR rates. Since part of the intake air is replaced by the exhaust gas, increasing EGR rate reduces the intake air mass flow rate. Compared with no use of EGR (EGR0), the average reductions found were of 3% for EGR2.5, 4% for EGR5, 7% for EGR7.5, and 9% for EGR10. The engine volumetric efficiency is also affected at the same proportions, as less air amount is admitted into the engine cylinders with increasing EGR rates. At a given EGR, the small variations of the intake air mass flow rate with engine load power are within the uncertainty of the measurements, as indicated by the error bars.

These variations are due to changes of the intake air temperature. With increasing load power the heat release rate is increased [42], and thus the ambient and intake air temperatures are also increased, reducing the intake air mass flow rate. To keep the intake air mass flow rate approximately constant, an order of decreasing load application was adopted during the tests. Similar to the intake air mass flow, the intake air volumetric flow slightly changed at a given EGR rate due to small variations in the intake air temperature and pressure with load variation. As in the case of the intake air mass flow, the changes in the volumetric flow at a fixed EGR were within the uncertainty of the measurements.

Figure 5 presents the variation in fuel conversion efficiency, normalized to the standard atmospheric conditions, for different loads and EGR rates. The use of EGR causes a negative effect on fuel conversion efficiency, being in agreement with the behaviour reported by Refs. [10, 24, 30–32]. The decrease of fuel conversion efficiency is mainly due to the reduction of air/fuel ratio (Fig. 6) [4].

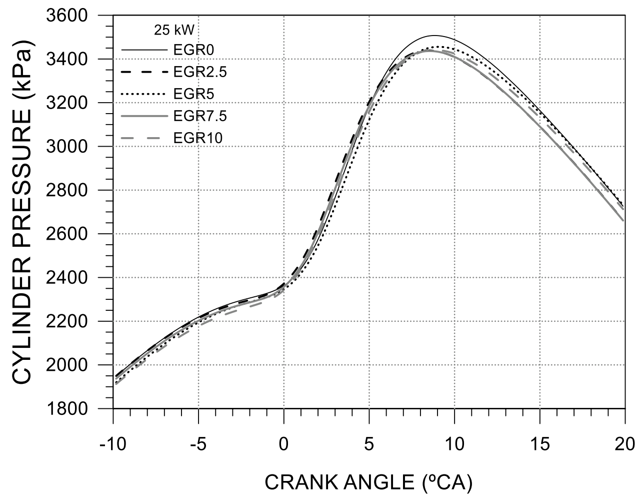

Fig. 2 In-cylinder pressure diagram at 25 kW for different EGR rates

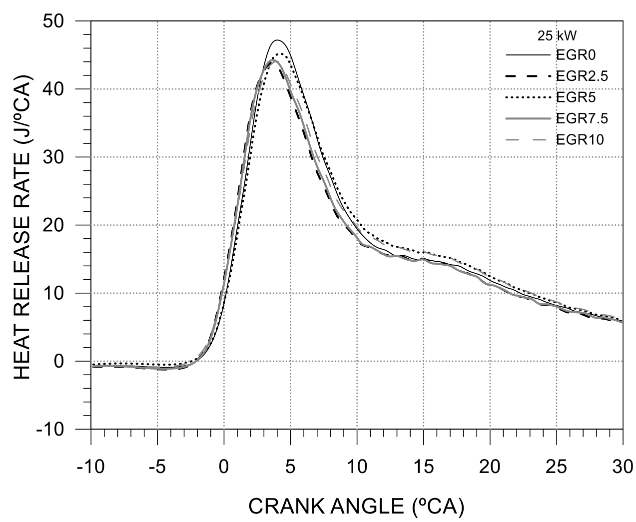

Fig. 3 Heat release rate curve at 25 kW for different EGR rates

Fuel conversion efficiency is not significantly affected by EGR only in the extremes of the load range investigated, at 5 and 30 kW, where the values are close to EGR0. For all intermediate loads fuel conversion efficiency decreases with the use of EGR. The maximum decrease was 5.7%, for operation with 10% EGR and 25 kW load. Thus, in general, it is not attractive to use high EGR rates at high loads because combustion tends to deteriorate, leading to reduced fuel conversion efficiency.

The effects of EGR on CO_2, CO and THC emissions are shown in Figs. 7, 8 and 9. In general, it is noticed that CO_2, CO and THC emissions increase with the use of EGR. The trend presented by CO_2 (Fig. 7) is explained by the fact that the fresh intake air contains negligible amounts of CO_2, while the EGR fraction carries a substantial amount of

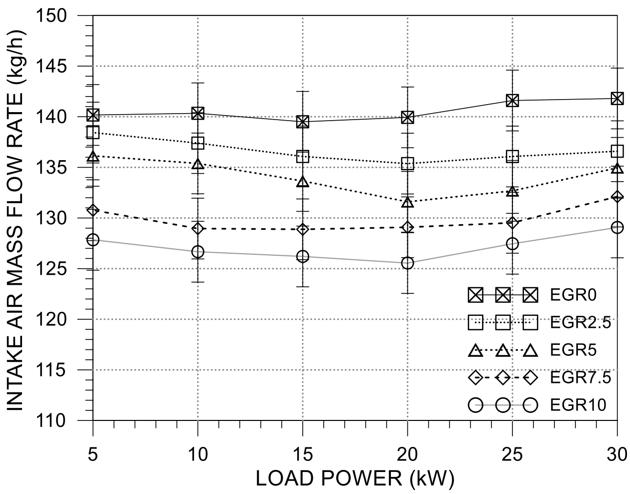

Fig. 4 Variation of intake air mass flow rate with EGR rate and load

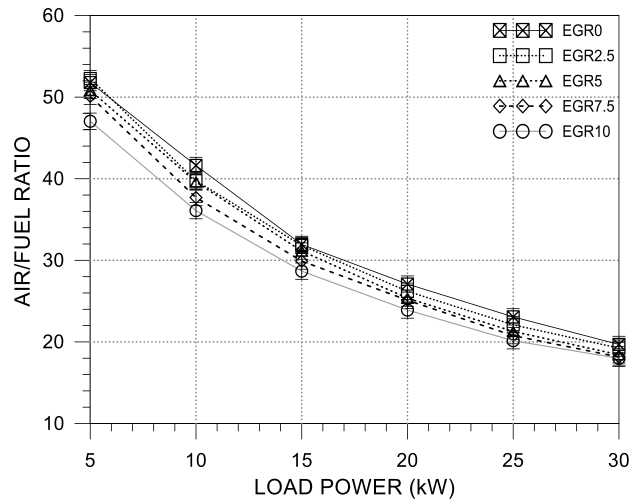

Fig. 6 Variation of mixture air/fuel ratio with EGR rate and load

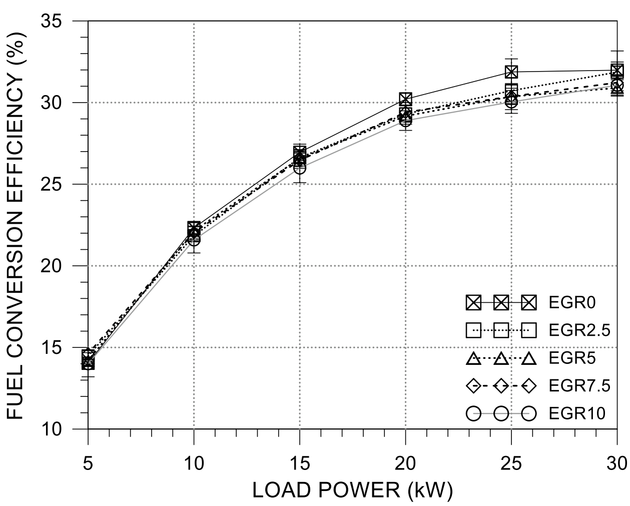

Fig. 5 Variation of fuel conversion efficiency with EGR rate and load

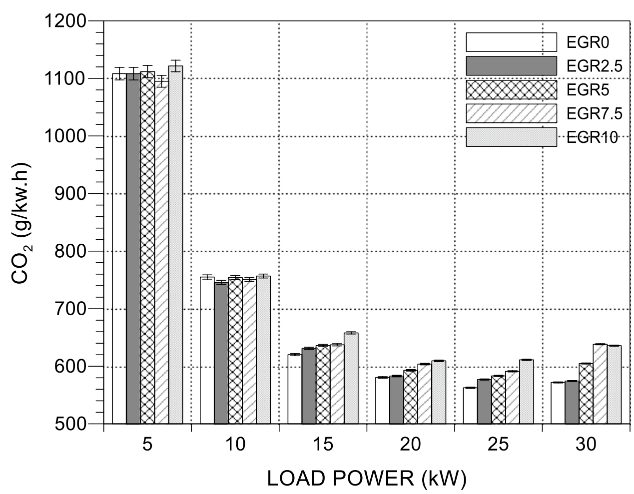

Fig. 7 Variation of carbon dioxide emissions with EGR rate and load

CO_2, which is higher with increasing EGR flow rate and engine load [15, 21]. The highest increases of CO_2 emissions were 11.6 and 11.2%, for 7.5% EGR and 10% EGR, respectively, at the load of 30 kW. At 10 kW and lower engine loads, the EGR rate did not significantly affect CO_2 emissions.

Carbon monoxide emissions result from incomplete combustion and are largely dependent on air–fuel ratio [6]. The increase of EGR rate reduces oxygen availability in the combustion chamber and decelerates the reaction rates of the air–fuel mixture, thus producing lower temperatures [3, 30]. In such a case, the flame propagation may not be sustained with relatively lean mixtures. Thus, the heterogeneous mixture does not burn completely, resulting in higher CO and THC emissions as observed in most situations (Figs. 8, 9), being in agreement with Refs. [10, 24, 30, 34]. The largest CO increment was observed for 10% EGR and 30 kW engine load, of 41.7% (Fig. 8).

With regard to THC-specific emissions, the largest increases in comparison with EGR0 were found for minimum EGR (EGR2.5) at any load, or maximum load (30 kW) at any EGR rate. The maximum increase recorded was 27.4%, for 2.5% EGR and 30 kW. Decreased THC emissions were observed with the use of 5% EGR and 10 kW load or lower, and 7.5% EGR with 25 kW load or lower. At high load, the increase of THC is explained by the higher fuel amount injected to meet the demand, also originating higher amounts of unburned fuel. With 2.5% EGR, the intake air charge and fuel injection amount were not substantially modified in comparison with EGR0 (Figs. 4, 5), but the small presence of the exhaust gas recirculated

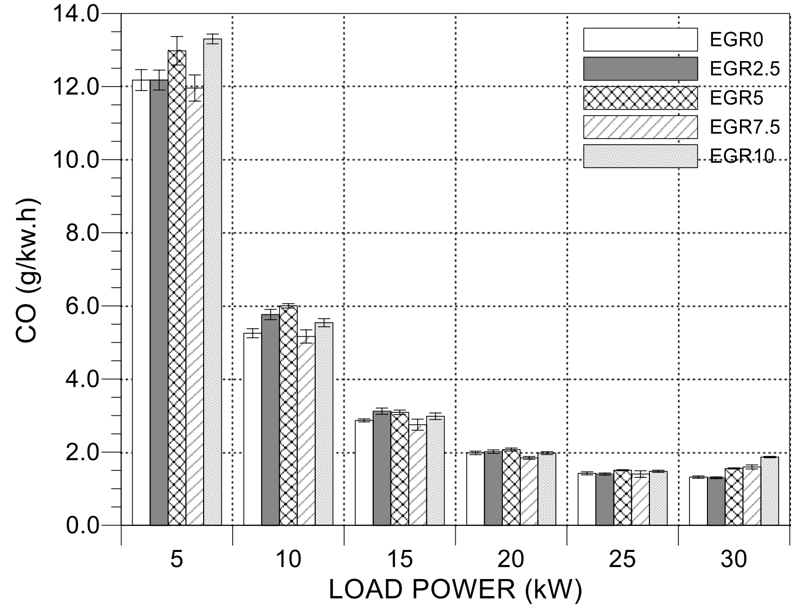

Fig. 8 Variation of carbon monoxide emissions with EGR rate and load

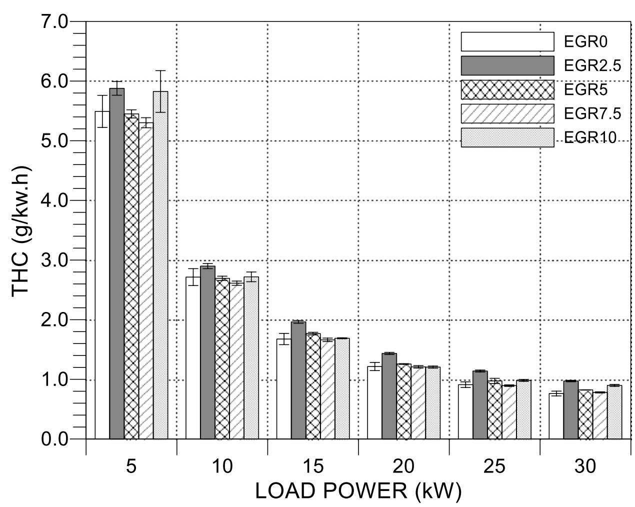

Fig. 9 Variation of total hydrocarbon emissions with EGR rate and load

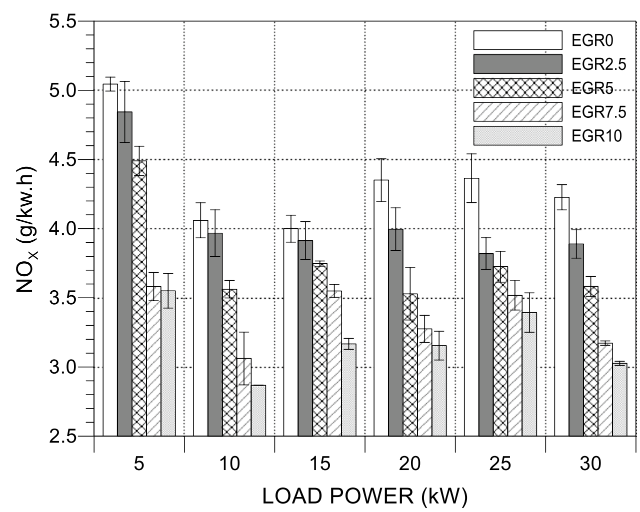

Fig. 10 Variation of oxides of nitrogen emissions with EGR rate and load

was enough to intensify incomplete combustion and generate unburned hydrocarbons. With higher EGR rates, there was a substantial reduction of the intake air to the cylinder (Fig. 4) and, therefore, oxygen availability in the gas. However, with high EGR rates, mixture enrichment (Fig. 5) using a fuel blend with an oxygenated fuel counterbalanced the awkward effects of low oxygen availability in the gas, not allowing hydrocarbon formation to increase.

Figure 10 shows that NO_X-specific emissions are reduced with increasing EGR rate for all engine load range investigated. This behaviour is justified by the reduction of oxygen availability due to the displacement of some of the oxygen in the fresh intake air charge by the recirculated exhaust gas [30, 43–48]. This causes a reduction in the local flame temperature because of the spatial broadening of the flame due to the reduction in the oxygen molar fraction [24]. Also, there is the thermal effect due to the increase in the average specific heat capacity of the gases in the combustion zone, since the recirculated exhaust gas contains CO_2 and H_2O with higher specific heat than that of air. Finally, there is a reduction in the combustion temperature due to endothermic chemical reactions, such as CO_2 and H_2O dissociation [4, 13]. Using 10% EGR, the reductions on NO_X emissions ranged from 20.8 to 29.6% for the different loads. Using 2.5% EGR, the decrease on NO_X remissions ranged from 2.2 to 12.5%.

4 Conclusions

The use of EGR was shown to be feasible for reduction of NO_X emissions from a diesel power generator with the adapted technology operating with B7. A reduction of nearly 30% of NO_X emissions was reached using 10% EGR rate. With 2.5% EGR, the maximum reduction of NO_X emissions was 12.5%. With increasing EGR rate, the in-cylinder peak pressure and the peak heat release rate decreased. In most situations, the use of EGR increased CO_2, CO and THC emissions, especially at high loads. However, under certain load conditions and EGR rates, decreased levels of those components were observed with the use of EGR. Based on these results, for simultaneous decrease of NO_X, CO and THC emissions, with only small increases on CO_2 emissions, if any, it is recommended the use of 7.5% EGR at low and moderate loads.

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References

1. Turns SR (2013) Introduction to combustion. Mc Graw-Hill, New York
2. Palash SM, Masjuki HH, Kalam MA, Masum BM, Sanjid A, Abedin MJ (2013) State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled Compression Ignition engines. Energ Convers Manag 76:400–420. doi:10.1016/j.enconman.2013.07.059
3. Bermúdez V, Lujan JM, Pla B, Linares WG (2011) Effects of low pressure exhaust gas recirculation on regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine. Energy 36:5655–5665. doi:10.1016/j.energy.2011.06.061
4. Hountalas DT, Mavropoulos GC, Binder KB (2008) Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions. Energy 33:272–283. doi:10.1016/j.energy.2007.07.002
5. Park SH, Junepyo C, Lee CS (2010) Effects of bioethanol-blended diesel fuel on combustion and emission reduction characteristics in a direct-injection diesel engine with exhaust gas recirculation (EGR). Energ Fuel 24:3872–3883. doi:10.1021/ef100233b
6. Park SH, Youn IM, Lee CS (2010) Influence of two-stage injection and exhaust gas recirculation on the emissions reduction in an ethanol-blended diesel-fueled four-cylinder diesel engine. Fuel Process Technol 91:1753–1760. doi:10.1016/j.fuproc.2010.07.016
7. Ishida M, Yamamoto S, Ueki H, Sakaguchi D (2010) Remarkable improvement of NO_X-PM trade-off in a diesel engine by means of bioethanol and EGR. Energy 35:4572–4581. doi:10.1016/j.energy.2010.03.039
8. He BQ (2016) Advances in emission characteristics of diesel engines using different biodiesel fuels. Renew Sust Energ Rev 60:570–586. doi:10.1016/j.rser.2016.01.093
9. Divekar PD, Chen X, Tjong J, Zheng M (2016) Energy efficiency impact of EGR on organizing clean combustion in diesel engines. Energ Convers Manage 112:369–381. doi:10.1016/j.enconman.2016.01.042
10. Kumar BR, Saravanan S, Rana D, Anish V, Nagendran A (2016) Effect of a sustainable biofuel—n-octanol—on the combustion, performance and emissions of a DI diesel engine under naturally aspirated and exhaust recirculation (EGR) modes. Energ Convers Manag 118:275–286. doi:10.1016/j.enconman.2016.04.001
11. Bozza F, De Bellis V, Teodosio L (2016) Potentials of cooled EGR and water injection for knock resistance and fuel consumption improvements of gasoline engines. Appl Energ 169:112–125. doi:10.1016/j.apenergy.2016.01.129
12. Mohammadi A, Ishiyama T, Kakuta T, Kee SS (2005) Fuel injection strategy for clean diesel engine using ethanol blended diesel fuel. SAE Technical Papers Series 2005-01-1725
13. Maiboom A, Tauzia X, Hétet JF (2008) Experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emissions of an automotive direct injection diesel engine. Energy 33:22–34. doi:10.1016/j.energy.2007.08.010
14. Millo F, Giacominetto PF, Bernardi MG (2012) Analysis of different exhaust gas recirculation architectures for passenger car Diesel engines. Appl Energ 98:79–91. doi:10.1016/j.apenergy.2012.02.081
15. Hebbar GS, Bhat AK (2013) Control of NO_X from a DI diesel engine with hot EGR and ethanol fumigation: an experimental investigation. Int J Automot Techn 14:333–341. doi:10.1007/s12239-013-0037-8
16. Asad U, Zheng M (2014) Exhaust gas recirculation for advanced diesel combustion cycles. Appl Energy 123:242–252. doi:10.1016/j.apenergy.2014.02.073
17. Ladommatos N, Abdelhalim SM, Zhao H, Hu Z (1996) The dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions-part 1: effect of reducing inlet charge oxygen. SAE Technical Papers Series 961165
18. Ladommatos N, Abdelhalim SM, Zhao H, Hu Z (1996) The dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions-part 2: effects of carbon dioxide. SAE Technical Papers Series 961167
19. Ladommatos N, Abdelhalim SM, Zhao H, Hu Z (1996) The Dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions-part 3: effects of water vapour. SAE Technical Papers Series 971659
20. Ladommatos N, Abdelhalim SM, Zhao H, Hu Z (1997) The dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions-part 4: effects of carbon dioxide and water vapour. SAE Technical Papers Series 971660
21. Zheng M, Reader GT, Hawley JG (2004) Diesel engine exhaust gas recirculation—a review on advanced and novel concepts. Energ Convers Manag 45:883–900. doi:10.1016/S0196-8904(03)00194-8
22. Abd-Alla GH (2002) Using exhaust gas recirculation in internal combustion engine: a review. Energ Convers Manag 43:1027–1042. doi:10.1016/S0196-8904(01)00091-7
23. Alriksson M, Rente T, Denbratt I (2005) Low soot, low NOx in a heavy duty diesel engine using high levels of EGR. SAE Technical Paper Series 2005-01-3836
24. Hussain J, Palaniradja K, Alagumurthi N, Manimaran R (2012) Effect of exhaust gas recirculation (EGR) on performance and

emission characteristics of a three cylinder direct injection compression ignition engine. AEJ 51:241–247. doi:10.1016/j.aej.2012.09.004
25. Li X, Xu Z, Guan C, Huang Z (2014) Impact of exhaust gas recirculation (EGR) on soot reactivity from a diesel engine operating at high load. Appl Therm Eng 68:100–106. doi:10.1016/j.applthermaleng.2014.04.029
26. Solaimuthu C, Ganesan V, Senthilkumar D, Ramasamy KK (2015) Emission reductions studies of a biodiesel engine using EGR and SCR for agriculture operations in developing countries. Appl Energ 138:91–98. doi:10.1016/j.apenergy.2014.04.023
27. Asad U, Kumar R, Zheng M, Tjong J (2015) Ethanol-fueled low temperature combustion: a pathway to clean and efficient diesel engine cycles. Appl Energ 157:838–850. doi:10.1016/j.apenergy.2015.01.057
28. Asad U, Tjong J, Zheng M (2014) Exhaust gas recirculation—Zero-dimensional modelling and characterization for transient diesel combustion control. Energ Convers Manage 86:309–324. doi:10.1016/j.enconman.2014.05.035
29. Schubiger R, Bertola A, Boulouchos K (2001) Influence of EGR on combustion and exhaust emissions of heavy duty DI-diesel engines equipped with common-rail injection systems. SAE Technical Papers Series 2001-01-3497
30. Agarwal D, Singh SK, Agarwal AK (2011) Effect of exhaust gas recirculation (EGR) on performance, emissions, deposits and durability of constant speed compression ignition engine. Appl Energ 8:2900–2907. doi:10.1016/j.apenergy.2011.01.066
31. Kumar BR, Saravanan S (2015) Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed DI diesel engine fueled with pentanol/diesel blends. Fuel 160:217–226. doi:10.1016/j.fuel.2015.07.089
32. Selim MYE (2003) A study of some combustion characteristics of dual fuel engine using EGR. SAE Technical Papers Series 2003-01-0766
33. Niemi SA, Paanu TPJ, Laurén MJ (2004) Effect of injection timing, EGR and EGR cooling on the exhaust particle number and size distribution of an off-road diesel engine. SAE Technical Paper Series 2004-01-1988
34. Wei H, Zhu T, Shu G, Tan L, Wang Y (2012) Gasoline engine exhaust gas recirculation-a review. Appl Energy 99:534–544. doi:10.1016/j.apenergy.2012.05.011
35. Hong SK, Lee KS, Song S, Chun KM, Chung D, Min S (2011) Parametric study on particle size and SOF effects on EGR cooler fouling. Atmos Environ 45:5677–5683. doi:10.1016/j.atmosenv.2011.07.036
36. Lee J, Min K (2014) A study of the fouling characteristics of EGR coolers in diesel engines. J Mech Sci Technol 28:3395–3401. doi:10.1007/s12206-014-0752-8
37. Planalto.gov.br. (2014) Lei Nr. 13033-Adição obrigatória de biodiesel ao óleo diesel. http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2014/Lei/L13033.htm. Accessed 30 Feb 2017
38. Salvador R, Bringhenti C, Tomita JT (2016) Characterization of an ethanol fueled heavy duty engine powering a generator set. Appl Therm Eng 102:1395–1402. doi:10.1016/j.applthermaleng.2016.03.107
39. Kline SJ, McClintock FA (1953) Describing uncertainties in single sample experiments. Mechanical Engineering 75:3–8
40. Öztürk E (2015) Performance, emission, combustion and injection characteristics of a diesel engine fueled with canola oil-hazelnut soapstock biodiesel mixture. Fuel Process Technol 129:183–191. doi:10.1016/j.fuproc.2014.09.016
41. Buyukkaya E (2010) Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel 89:3099–3105. doi:10.1016/j.fuel.2010.05.034
42. Oliveira A, Morais AM, Valente OS, Sodre JR (2016) Combustion, performance and emissions of a diesel power generator with direct injection of B7 and port injection of ethanol. Brazil J Mech Sci Eng. doi:10.1007/s40430-016-0667-7
43. Choi S, Park W, Lee S, Min K, Choi H (2011) Methods for in-cylinder EGR stratification and its effects on combustion and emission characteristics in a diesel engine. Energy 36:6948–6959. doi:10.1016/j.energy.2011.09.016
44. Guo M, Fu Z, Ma D, Ji N, Song C, Liu Q (2015) A short review of treatment methods of marine diesel engine exhaust gases. Procedia Eng 121:938–943. doi:10.1016/j.proeng.2015.09.059
45. Stein HJ (1996) Diesel oxidation catalysts for commercial vehicle engines: strategies on their application for controlling particulate emissions. Appl Catal B-Environ 10(1–3):69–82. doi:10.1016/0926-3373(96)00024-0
46. Resitoglu IA, Altinisik K (2015) The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technol Envir 17:15–27. doi:10.1007/s10098-014-0793-9
47. Zervas E (2008) Impact of different configurations of a diesel oxidation catalyst on the CO and HC tail-pipe emissions of a Euro4 passenger car. Appl Therm Eng 28:962–966. doi:10.1016/j.applthermaleng.2007.06.033
48. Park Y, Bae C (2014) Experimental study on the effects of high/low pressure EGR proportion in a passenger car diesel engine. Appl Energy 133:308–316. doi:10.1016/j.apenergy.2014.08.003