Investigation of Steam Injection with Exhaust Gas Recirculation (EGR) on a Diesel Engine

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Abstract: - Steam injection with EGR is carried out on a direct injection diesel engine to decrease NO_x emissions. The obtained results have been compared with standard diesel in terms of performance and NO_x, CO, CO_2, HC emissions. In the experimental results, it was determined that NO_x emissions reduced up to 77.3% at the condition of steam injected diesel engine with EGR when compared to standard diesel mode. Specific fuel consumption increase at 20% steam injection (S20) and two EGR ratios (%20 and30%). Comparing with NO_x and SFC, the optimum point is found at 2000 rpm with 3.3% reduces in SFC and 50.4% decrease in NO emissions with S20-E10 mode.In S20 condition, with 6.1% reduction in SFC, NO_x reduce 7.6% at 2400 rpm. In conclusion, steam injection with EGR gives good results in NO_x emissions and SFC. The optimum point was found at S20+E10.

Key-Words: -Diesel engine, pollutant emissions, EGR, steam, performance, NO_x

1 Introduction

In recent years, diesel engines have been still the most economical on fuel in respect of internal combustion engines in commercial transportation as sea and land transportation. However, in the light of current regulations with regard to reduction of pollutant emissions in marine diesel engines like MARPOL (International convention for the prevention of pollution from ships), real-engine designers have to develop new in-cylinder strategies or after treatment devices.

In this study, the literature can be classified into three groups as water injection, steam injection and EGR. The first group is water injection into combustion chamber directly, as emulsified or fumigation to the intake manifold. The objective of the water injection is to decrease NO_x emissions along with using diesel oil with water as maximum flame temperature reduces [1,2]. In these studies conducted by the authors, it wasstated that NO_x emissions decrease [1,3,4], HC and CO emissions and SFC improves when water injection is applied to diesel engines [5,3,6]. However,in fumigation method, condensed water nominately deteriorate the specification of oil by mixing with lubricating oil and consequently it was observed that wear rate of moving part of engine increases [7].

The second group is water injection into intake manifold as a steam phase. Parlak et al. observed that NO_x emissions decrease up to 33%, effective power and torque increases up to 3% and SFC decrease up to 5% as a result of full load tests with electronically controlled steam injection system [8,9]. Murthy et al. determined that in the event of solar generated steam injection to diesel engine,NO emissions and exhaust temperature reduce; soot emissions, thermal efficiency, power and SFC increase at full load conditions [10].

The last group is EGR technology to reduce NO_x emissions [11,12,13]. EGR has caused a decrease in flame temperature within the combustion chamber owing to the lower oxygen mole fraction and the higher heat capacity of CO_2 and H_2O in comparison to air and owing to these effects of EGR, NO_x formation rate decrease [14]. Consequently, from the literature, NO_x emissions reduces significantly [11,12,13,15,16,17], CO emissions increase [15,16], HC emissions increase [15,16,18], smoke emissions decrease [17,18,19], PM emissions worsen [21,22] and specific fuel consumption (SFC) increase [15,20,21,22] with EGR application.

As a matter of fact, there is no study to investigate experimental of steam injected diesel engine with EGR on performance and emission parameters. Hence, in this study, electronically controlled steam injection system developed by Parlak et al. [8] has been extended by using EGR to investigate engine torque, effective power and efficiency, SFC and NO, CO, CO2, HC emissions of a DI diesel engine.

2 Experimental Set-up

The experiments were carried out with a single cylinder, naturally aspirated, four-stroke, and water cooled, DI Diesel engine with a bowl in piston combustion chamber. Table 1 and Figure 1 show the engine specification and experimental set-up, respectively.

Fig. 1. Experimental Set-up

Table 1. Engine specification

Engine Type	Super Star
Bore [mm]	108
Stroke [mm]	100
Cylinder Number	1
Stroke Volume [dm^3]	0,92
Power, 1500 rpm, [kW]	13
Injection pressure [bar]	175
Injection timing [Crank Angle]	35
Compression ratio	17
Maximum speed [rpm]	2500
Cooling	Water
Injection	Direct Injection

In order to measure brake torque, the engine is coupled with a hydraulic type dynamometer of 50 kW absorbing capacity using an “S” type load cell with the precision of 0.1 N. Before starting the experiments, load cell is calibrated sensitively.

In this study, MRU Spectra 1600 L type gas analyzer was used so as to measure exhausts. Before experiments, emission and smoke device were calibrated.

Having 99% purity Linde Gas brand CO_2 gas was used for EGR application due to the most component in exhaust gases and having calibrated to control EGR ratio.

Needham vd.[23]’ s method was used in order to determine the amount of CO_2 to intake manifold. EGR percentage;

$$EGR(\%) = \frac{CO_{2(intakemanifold)} - CO_{2(surroundings)}}{CO_{2(exhaustmanifold)}} x100 (1)$$

Where $CO_{2(surroundings)}$ is the reference CO_2 percentage in surroundings. In this study, this value was neglected owing to being 0.03% in the literature [24]. EGR ratios were determined with a volume ratio of CO_2 value. In the experiments, 10%, 20% and 30% EGR ratios were carried out.Experiments were done in variable speeds 1200, 1400, 1600, 1800, 2000, 2200 and 2400 rpm and full load condition.

After standard diesel tests were carried out performance and emission values of the engine tested for three EGR ratios (10-20-30%) were compared with those of standard diesel running with S20 steam. The experiments were conducted for full load conditions. S20 is chosen as it is optimum steam ratio in terms of performance and emissions, which is found in the study conducted by Parlak et al. [8,9].

3 Results and Discussion

In this study, the effects of steam injected diesel engine with EGR on performance and emission values has been investigated. Obtained results are compared with those of standard diesel engine.

3.1 Engine Performance Parameters

3.1.1 Engine Torque

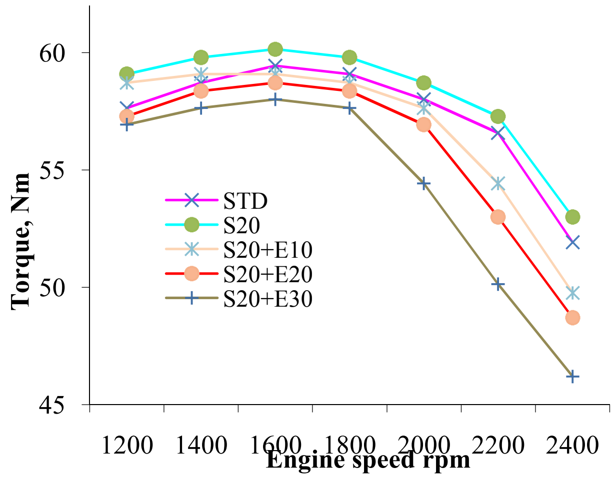

Fig.2. Engine Torque for S20+10-20-30% EGR

Fig. 2 shows the experimental results of engine torque with condition of20% steam injection (S20) and three EGR ratios (10%,20% and 30%) . As a results of experimental studies, torque reducedwith

EGR. Maximum torque is found as 60.2 Nm and 59.4 Nm at 1600 rpm with S20 and S20+E10, respectively. In comparison to standard values, while the highest reduce in torque is 11.4% at 2200 rpm with S20+E30; the lowest decrease is 0.6% at 1600 rpm with S20+E10.On the contrary, 1.9% and 0.6% increase occur at 1200 and 1400 rpm in S20+E10, respectively.

3.1.2 Effective Power

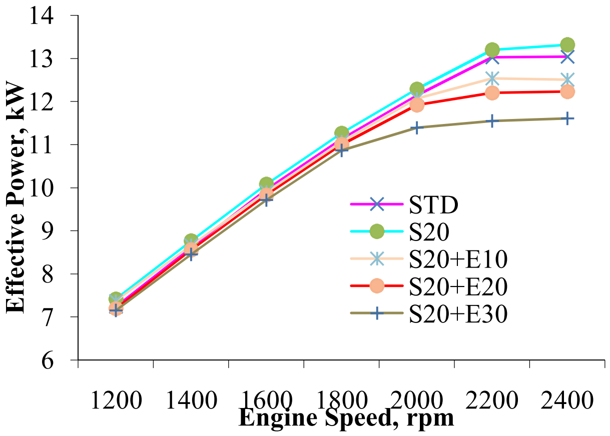

Fig.3. Effective Power for S20+10-20-30% EGR

Fig. 3 shows the experimental results of effective power with condition on 20% steam injection (S20) and 10-20-30% EGR. According to experimental results, power reduces with EGR. Maximum power is found as 13.3kW and 12.5kW at 2400 rpm with S20 and S20+E10 respectively. In comparison to standard values, while the highest reduce in power is 11.4% at 2200 rpm with S20+E30; the lowest decrease is 0.6% at 1600 rpm with S20+E10. On the contrary, 1.9% and 0.6% increase occur at 1200 and 1400 rpm in S20+E10 respectively.

3.1.3 Specific Fuel Consumption (SFC)

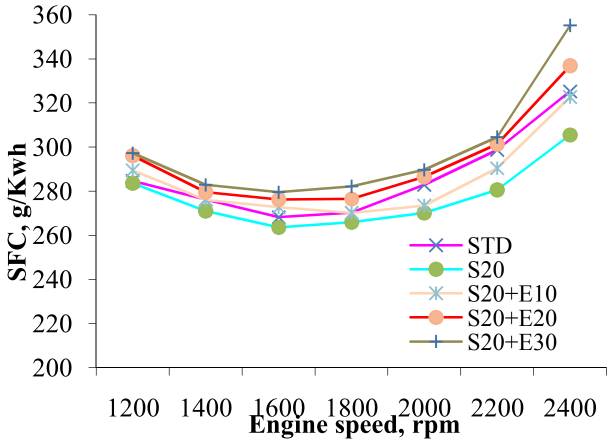

Fig.4.SFC for S20+10-20-30% EGR

In the Fig.4, experimental data of specific fuel consumption (SFC) is given comparatively. As can be seen from the figure that SFC increases with EGR. The lowest SFC is 263.7 g/kWh at 1600 rpm and 270.1 g/kWh at 1800 rpm with S20 and S20+E10 respectively. According to standard SFC, the highest increase is 9.2% at 2400 rpm with S20+E30, the lowest change is 0.1% at 1400 rpm with S20+E10. In contrast, 3.3% reduce in SFC occurs at 2000 rpm in S20+E10.

When considerable decrease in NO_x emissions is considered with S20+E10 (pls see the Fig.5), the decrease in brake power and brake torque and increase in SFC can be neglected.

3.2 Emission Parameters

3.2.1 In cylinder Temperature and NO_x

The comparison of in-cylinder temperatures of experimental data at full-load conditions for the engine speed rates tested is given in the Fig.4. The effects of 20% steam injection and various EGR ratios on lowering in cylinder gas temperature steam injection are clearly shown in the figure.

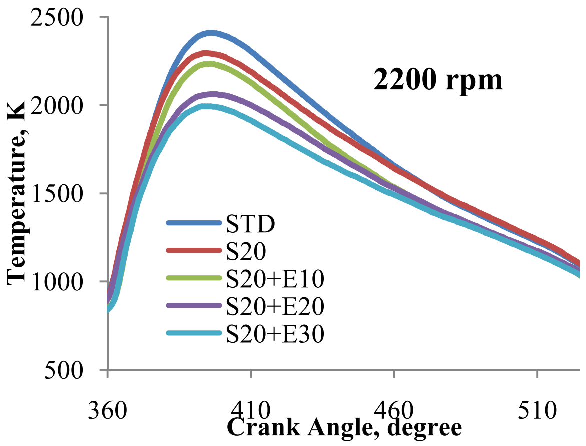

Fig.5. Temperature for S20+10-20-30% EGR

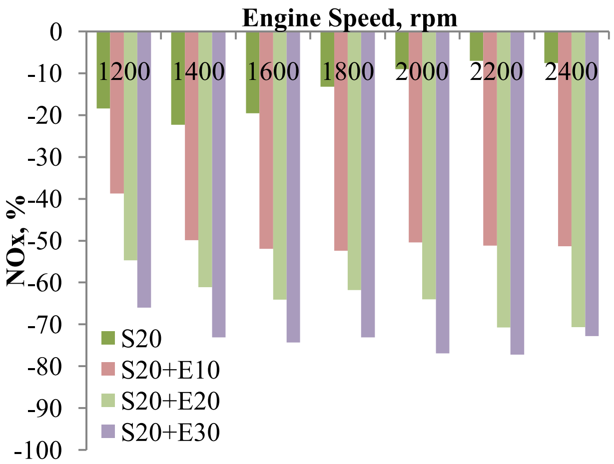

Fig.6.NO_x emissions for S20+10-20-30% EGR

Fig.5 gives the experimental data of NO_x emissions percentage changes with regard to standard condition. As can be seen from the Figure, steam injection and EGR considerably caused to reduce in NO_x emissions as the peak temperatures decrease.

The figure shows that NO_xemissions decrease at all engine speeds with steam injection and EGR. The minimum NO_x is 132 ppm at 2200 rpm with S20+E30. According to standard NO_x emission values, the highest change is 77.3% at 2200 rpm with S20+E30, the lowest change is 7% at 2200 rpm with S20.

3.2.2 CO and CO_2

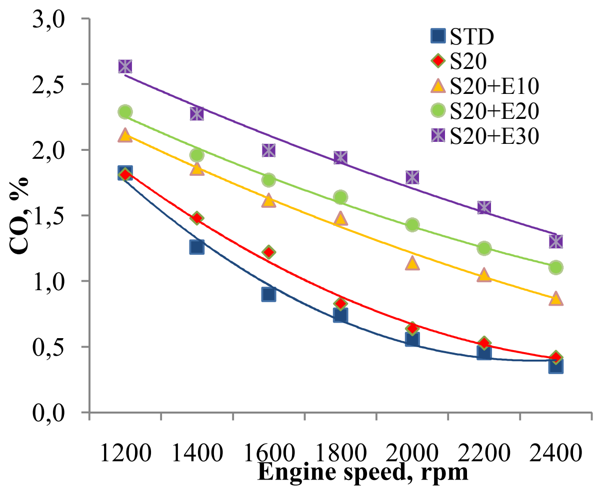

Fig.7.CO emissions for S20+10-20-30% EGR

Figure 6 compares steam injected and EGR condition diesel engine with CO emissions of standard one.. The CO emissions enhance with optimum steam injection rate and EGR at all engine speeds. However, it is seen that the increase in the emission is within the limits of uncertainty when considering measurement accuracy. Besides, in the experiments, considering 99% purity CO_2 gas is routing into intake manifold, the increase in CO emissions is in a normal rate. The minimum CO emission is 0.35%, 0.42% and 0.87% at 2400 rpm with standard, S20 and S20+E10 respectively.

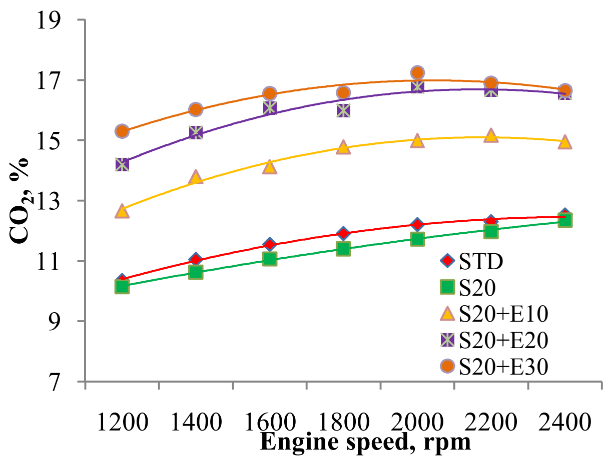

Fig.8.CO_2 emissions for S20+10-20-30% EGR

Figure 7 compares CO_2 emissions of standard, steam injected and EGR condition diesel engine. The CO_2 emissions increase with optimum steam injection rate and EGR at all engine speeds.Furthermore, in the experiments, considering 99% purity CO_2 gas was routing to intake manifold, the increase in CO_2 emissions were in a normal rate. The minimum CO_2 emission is 10.35%,10.15%

and12.66% at 1200 rpm of standard, S20 and S20+E10 respectively.

3.2.3 HC

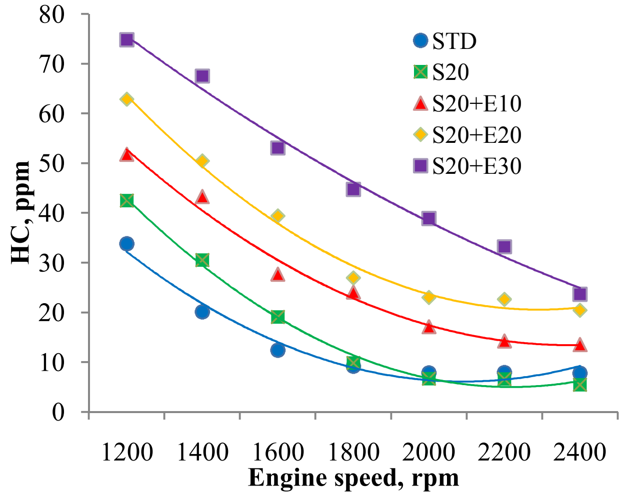

Fig.9.HC emissions for S20+10-20-30% EGR

Figure 8 compares HC emissions of standard, steam injected and EGR condition diesel engine. The HC emissions increase with EGR at all engine speed. However, it is seen that the changes in the emission values of diesel engines are within the limits of uncertainty when considering measurement accuracy. Moreover, in the experiments, considering 99% purity CO_2 gas was routing into intake manifold, the increase in HC emissions were in a normal rate. The minimum HC emission is 7.8ppm, 5.5 ppm and 13.5 rpm at 2400 rpm of standard, S20 and S20+E10, respectively.

4 Conclusion

In this study, the effects of electronically controlled steam injection with EGR on performance and emissions have been investigated.

When comparing with the standard values, there is a significant reduction in NO_x emissions. It is clear that SFC increases with EGRexcept some engine speeds in S20+E10. Whilst comparing NO_x and SFC, the optimum point is at 2000 rpm with 3.3% decrease in SFC and 50.4% decrease in NO emissions with S20+E10.In S20 condition, with 6.1% reduction in SFC, NO_x reduce 7.6% at 2400 rpm. Consequently, steam injection with EGR gives good results in NO_x emissions and SFC. The optimum point was found at S20+E10.

Therefore, this study may be carried out to the engineering applications to decrease NO_x emissions and a leading essential for the real-engine designers by considering the effects of steam injection with EGR into the engine cylinder.

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References:

[1] N. Samec, K. Breda, R.W. Dibble, Numerical and Experimental Study of Water/Oil Emulsified Fuel Combustion in a Diesel Engine, *Fuel*,Vol.81, 2002,pp.2035-2044.

[2] F. Bedford, C. Rutland, P. Dittrich, A. Raab, F. Wirbelit, Effects of direct water injection on DI Diesel Engine Combustion, *SAE paper*, 2000-01-2938.

[3] C.Y. Lin, K.H. Wang, Diesel Engine Performance and Emission Characteristics Using Three-Phase Emulsions as Fuel, *Fuel*,Vol.83, 2004,pp.537-545.

[4] X. Tauzia, A. Maiboom, S.R. Shah, Experimental Study of Inlet Manifold Water Injection on Combustion and Emissions of an Automotive Direct Injection Diesel Engine, *Energy*,Vol.35, 2010,pp.3628-3639.

[5] M. Abu-Zaid, Performance of Single Cylinder, Direct Injection Diesel Engine Using Water Fuel Emulsion, *Energy Conversion and Management,*Vol.45, 2004,pp.697-705.

[6] A. Alahmer, J. Yamin, A. Sakhrieh, M.A. Hamdan, Engine Performance using Emulsified Diesel Fuel, *Energy Conversion and Management*,Vol.51, 2010,pp.1708-1713.

[7] G.H. Abd-Alla, H.A., Soliman, O.A. Badr, M.F. Abd-Rabbo, Effects of Diluent Admissions and Intake Air Temperature in Exhaust Gas Recirculation on the Emissions of an Indirect Injection Dual Fuel Engine, *Energy Conversion and Management,*Vol.42, 2001,pp.1033-1045.

[8] A. Parlak, V. Ayhan, Y. Üst, B. Şahin, İ.Cesur, B. Boru, G. Kökkülünk, New method to reduce NO_x emissions of diesel engines: electronically controlled steam injection system, Journal of the Energy Institute,Vol.85, 2012,pp.135-139.

[9] A. Parlak, V. Ayhan, B. Şahin, İ.Cesur, B. Boru, G. Kökkülünk, The Effects of theNew Developed Electronic Controlled Steam Injection System on NO_x Emissions of a Single

ISBN: 978-1-61804-132-6

Cylinder Diesel Engine, 13th International Conference Maritime Transport and Infrastructure 2011, Riga.

[10] Y.V.V.S. Murthy, G.Y.K. Sastry, M.R.S. Satyanaryana, Experimental Investigation of Performance and Emissions on low Speed Diesel Engine with Dual Injection of Solar Generated Steam and Pongamia Methyl Ester, Indian Journal of Science and Technology,Vol.4, 2011,pp.29-33.

[11] G.H. Abd-Alla, H.A. Soliman, O.A. Badr, M.F.Abd-Rabbo, Effects of Diluent Admissions and Intake Air Temperature in Exhaust Gas Recirculation on the Emissions of an Indirect Injectıon Dual Fuel Engine, *Energy Conversion and Management*, Vol. 42, 2001,pp.1033-1045.

[12] J.W. Heffel, NO_x Emission Reduction in a Hydrogen fuelled Internal Combustion Engine at 1500 rpm using Exhaust Gas Recirculation, *International Journal of Hydrogen Energy*, Vol.28, 2003,pp.901-908.

[13] J.W. Heffel, NO_x Emission Reduction in a Hydrogen fuelled Internal Combustion Engine at 3000 rpm using Exhaust Gas Recirculation, *International Journal of Hydrogen Energy*, Vol.28, 2003,pp.1285-1292.

[14] O. Angrill, H.Geitlinger, T. Streibel, R.Suntz, H.Bockhorn,Influence of Exhaust Gas Recirculation on Soot Formation in Diffusion Flames, *Proceedings of the combustion Institute*, Vol. 28, 2000, pp.2643-2649.

[15] A. Maiboom, X.Tauzia, J-F.Hetet,Experimental Study of Various Effects of Exhaust Gas Recirculation (EGR) on Combustion and Emissions of an Automotive Direct Injection Diesel Engine, *Energy*, Vol.33,2008, pp.22-34.

[16] H.E. Saleh,Experimental Study on Diesel Engine Nitrogen Oxide Reduction Running with Jojoba Methyl Ester by Exhaust Gas Recirculation, *Fuel*, Vol.88, 2009, pp.1357-1364.

[17] R. Kiplimo, E. Tomita, N. Kawahara, S.Yokobe,Effects of Spray Impingement, Injection Parameters, and EFR on the Combustion and Emission Characteristics of a PCCI Diesel Engine, *Applied Thermal Engineering*,2011,doi:10.1016/j.applthermaleng.2011.11.011.

[18] S.S. Nathan, J.M.Mallikarjuna, A.Ramesh, Effects of Charge Temperature and Exhaust Gas Re-Circulation on Combustion and Emission Characteristics of an Acetylene Fuelled HCCI Engine, *Fuel*, Vol.89, 2010,pp.515-521.

[19] H.Peng, Y. Cui, L.Shi, K.Deng, Effects of Exhaust Gas Recirculation (EGR) on Combustion and Emissions During Cold Start of Direct Injection (DI) Diesel Engine, Energy, Vol.33, 2008,pp.471-479.

[20] L.Shi, Y.Cui, K.Deng, H.Peng, Y.Chen, Study of Low Emission Homogeneous Charge Compression Ignition (HCCI) Engine Using Combined Internal and External Exhaust Gas Recirculation (EGR), *Energy*, Vol.31, 2006,pp.2665-2676.

[21] N.Ladommatos,S.M.Abdelhalim,H.Zhao, Z. Hu, The effects of carbon dioxide in exhaust gas recirculation on Diesel engine emission. *ProcInstnMechEngng part D J. Automative Eng.,*Vol. 212, 1998, pp.25-42.

[22] C.Beatrice, C. Bertoli, N.C. Cirillo, N.D. Giacomo, R. Innocente, Influence of high EGR rate on emissions of a DI Diesel engine,*ASME ICE Div*,10/02-06/94, 1998, pp.193–201.

[23] J.R. Needham, A.J. Nicol, C.H. Such, Low Emission Heavy Duty Diesel Engine for Europe, *SAE Paper*, No.932959, 1993.

[24] S. Çetinkaya, *Termodinamik*, Nobel Yayınları, 1999, (in Turkish).