Effect of Dissolved CO 2 in Diesel Fuel on Engine Performance and Emissions

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Effect of Dissolved CO_2 in Diesel Fuel on Engine Performance and Emissions

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Abstract

This study represents the effect of enriched diesel with CO_2 on a real diesel engine, tests for comparison between pure diesel and enriched diesel with CO_2 at 4 various mass fractions were performed. To map the engine performance, three throttles were chosen, in order to cover the speed range the throttles were full, 85%, and 70%. Five different speeds were used at each throttle in order to cover the whole range of these speeds. Engine performance was studded and a comparison for the torque, brake power, thermal efficiency, and specific fuel consumption were performed, as well as the effect of enriching diesel with CO_2 on engine emissions was also studied, NO_x and smoke contents, as well as CO_2, CO, and HC.

Introduction

In diesel engine or compression ignition engine, fuel is injected by the fuel- injection system into the engine cylinder toward the end of compression stroke, just before the desired start of combustion. The liquid fuel is injected at high velocity as one or more jets through small orifices or nozzles in the injector tip, and atomizes into small drops and penetrates into the combustion chamber. The fuel vaporizes and mixes with the high-temperature high-pressure cylinder air. Since the air temperature and pressure are above the fuel's ignition point, spontaneous ignition of portion of the already-mixed fuel and air occurs after a delay period of a few crank angles degrees. The cylinder pressure increases as combustion of the fuel-air mixture occurs. The consequence compression of the under burned portion of the charge shortens the delay before ignition for the fuel and air which has mixed to within combustible limits, which then burns rapidly [1].

It is well known that atomization behavior and spray characteristics dominate the ignition process, combustion and emission levels of a particular diesel engine. Zhen et al. [2] studied the variation of spray patterns which shows that the resulting droplet size is much smaller for the high gas concentrations. The spray angle is maximized with the increase of concentration of dissolved gas, while Souter mean diameter is decreased.

The effect of CO_2 concentration in the fuel on flame structure was studded by Xiao et al. [3]. He shows that the low temperature flame length increases with the increase of CO_2 concentration in the fuel under the same conditions of injection pressure. This is due to two factors. One is that the separation of CO_2 gas from the jet dilutes the oxygen concentration, which is called dilution effect, and the other is the higher specific heat capacity of CO_2 in comparison with that of the oxygen it replaces (thermal effect), which makes the temperature lower and delays the formation rate of flame soot near the nozzle exit. It was shown also that when increasing the dissolved CO_2 concentration, the flame length will decrease. The reason may be that the axial velocity would be reduced and the spray is finer with more CO_2 counted in the diesel fuel (this was validated by PDA measurements). The high temperature flame length decreases with the increase of CO_2 concentration in the diesel fuel.

The presence of CO_2 mixed with fuel in the combustion process inside the diesel engine has several effects; thermal, chemical, and atomization effects. The thermal effect could be summarized by the high specific heat capacity of CO_2 (1.371 kJ/kg K at 2000 K, compared to 1.181 and 1.284 kJ/kg K for the O_2 and N_2 respectively at the same temperature) [4]. This will lead to a reduction in the flame temperature,

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hence a reduction in NO_x. The chemical effect might be summarized in by processes during the combustion stage, and the direct and indirect oxidation. The direct oxidation process asserts that CO_2 will act as oxidizer to oxidize soot formed in fuel combustion; this CO_2 is expected to dissociate to CO and O radical under high temperature field. The indirect oxidation asserts that the presence of CO_2 will enhance local O, OH radical concentrations which play an important role in oxidation of soot. Both oxidations depend on the concentration of CO_2 in the fuel. Moreover, some studies have reported that CO_2 component could reduce soot emission directly by the reaction of $C+ CO_2=2CO$ which is called Boudouard reaction [5]. The CO_2 enrichment resulting from the flash vaporization of CO_2 and micro mixing of CO_2 with fuel may help to promote both direct and indirect oxidation of smoke. In the injection process inside the combustion chamber, CO_2 gas will be generated through the flash boiling or separation process; this will form a rapid evaporation spray which suppresses the formation of soot [6].

This explanation of chemical effect might lead to the reduction of CO_2 and HC concentrations, and an increase in CO concentration in the products of combustion. Noting that in diesel engine CO content in products is in its minor values and has no significant effect.

Experimental Setup

A 2500cc Ford diesel engine test bed was prepared to be tested under the various fuel compositions (pure diesel and enriched diesel with various CO_2 concentrations). This engine is already equipped with an hydraulic dynamometer to measure the torque in Nm, a speedometer to measure the engine speed in rpm, an arrangement for fuel metering, an exhaust gas analyzer to measure the exhaust gas contents and its concentrations, and a smoke meter to measure the smoke particles content. An additional setup to apply fuel enriched with CO_2 was designed and added to the engine to be able to compare its characteristics and emissions for the various fuel contents. This setup is photographed and shown in figure 1a and b.

Dissolving CO_2 into fuel prior to introducing it into the engine was performed inside a special pressure vessel designed for this purpose. This vessel has three passages: the first is for filling the fuel, the second is for introducing CO_2 into the bottom of the vessel, and the third passage is the delivery line from the bottom of the vessel. CO_2 gas is introduced to the fuel from a high pressure vessel contains CO_2 which is available for this purpose.

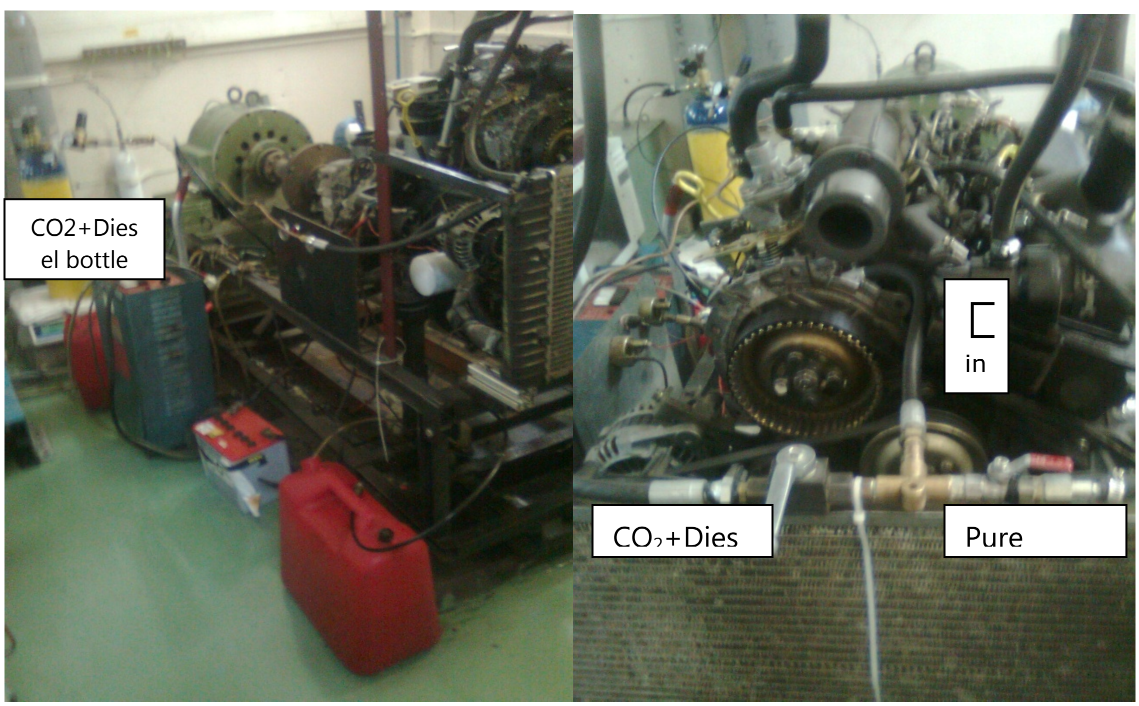

Figure 1: (a) Mixture bottle and supply line (b) Change over valves

Tests for comparison between pure diesel and enriched diesel with CO_2 at 4 various mass fractions were performed. These mass fractions were 2, 3.4, 5.1, and 6.7% of CO_2 content which are referred to pressures of 10, 15, 20, and 25 bar respectively. These mass fractions were produced in the solubility experiment that was done earlier in a different part of this research. To map the engine, three throttles were chosen in order to cover the speed range; the throttles were full, 85%, and 70%. Five different speeds were used at each throttle in order to cover the whole range of these speeds. The following steps for the engine runs at each throttle were performed:

1- Running the engine at pure diesel until reaching the steady state conditions and the engine operating temperature.
2- At a certain throttle the required speed was got by the dynamometer load adjustment.
3- Readings of torque, fuel mass flow, air mass flow, exhaust gasses, and smoke were registered when they are stable.
4- For exactly the same conditions at the time of test, the change over from pure diesel to enriched diesel with CO_2 was taking its place by closing pure diesel valve and opening the enriched fuel valve while the engine was running.
5- When all measuring parameters were settled down, the new readings for the mentioned parameters were registered; this insured a realistic comparison.

This procedure was followed for each run in order to get a realistic effect of the enriched fuel with CO_2.

Effect of CO_2 Content on Engine Performance

Figure 2 shows the torque comparison for the pure diesel and various mass concentrations of enriched diesel with CO_2, for the full throttle; a slight increase of torques were reported along the various speeds, for the throttles of 85 and 70m%. The increase in torques are more obvious; the maximum reported torque increase was 16% at 70% throttle and 1600 rpm, that was the 6.7% mass fraction of CO_2.

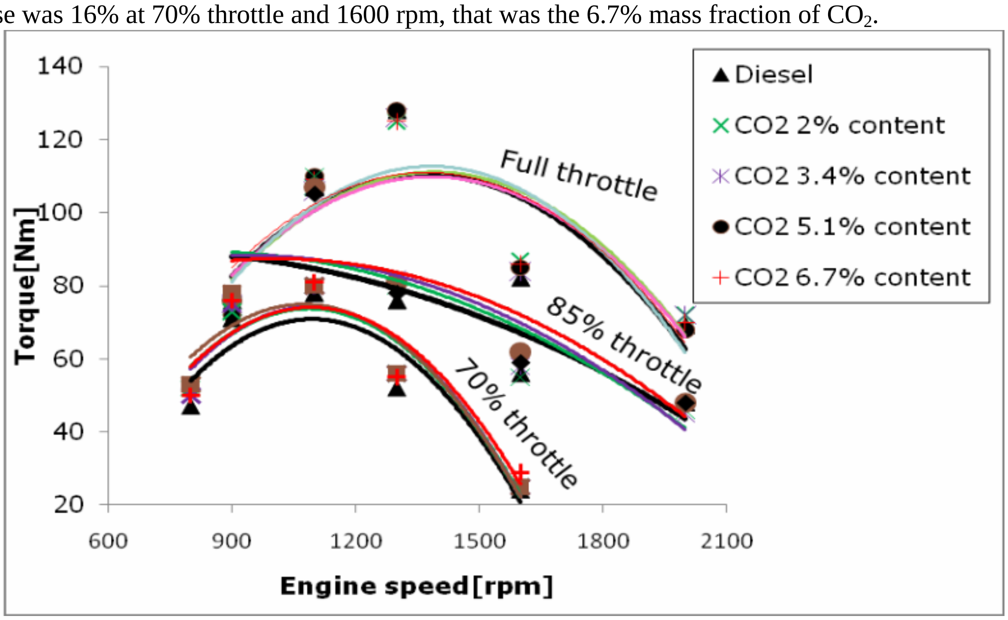

Figure 2: Torque versus speed for pure diesel and various concentrations of CO_2.

Brake power for each run was calculated due to the following formula:

$$b.P = T * \omega = T * \frac{2\pi N}{60} \quad \text{(kW)} \qquad (1)$$

where P is the power, T is the torque, ω is the angular velocity, and N is the engine speed.

The power ratio was calculated and registered relative to the base of pure diesel power. The power ratio is similar to that of torque ratio as shown in figure 3.

Brake thermal efficiency for each run was calculated due to the formula:

$$\eta_b = \frac{b.P}{m_f * C.V} \tag{2}$$

Where η_b is the brake thermal efficiency, *b.P* is the brake power, m_f is the mass flow rate of fuel, and *C.V* is the calorific value of diesel which is 42500 kJ/kg [1]. The maximum brake thermal efficiency ratio registered 18% increase,. The average thermal efficiency increase for all the cases was 6%. It is worth noting that mass of fuel measured was including both diesel and CO_2, in mass calculations the CO_2 content was subtracted from the total mass and applied in the above equation. Brake thermal efficiency ratio results are presented in figure 4. For the 85% throttle, thermal efficiency was increasing for all the speeds.

Brake specific fuel consumption (bsfc) is an important parameter representing the engine performance; it is defined by the following equation:

$$bsfc = \frac{m_f}{b.P * C.V} \tag{3}$$

Figure 5 shows the effect of CO_2 concentration in diesel on the bsfc for the whole of speed range; the best bsfc registered is 16%, and the average bsfc improvement is 5%. At 1300 rpm, all concentrations of CO_2 registered an improvement in bsfc.

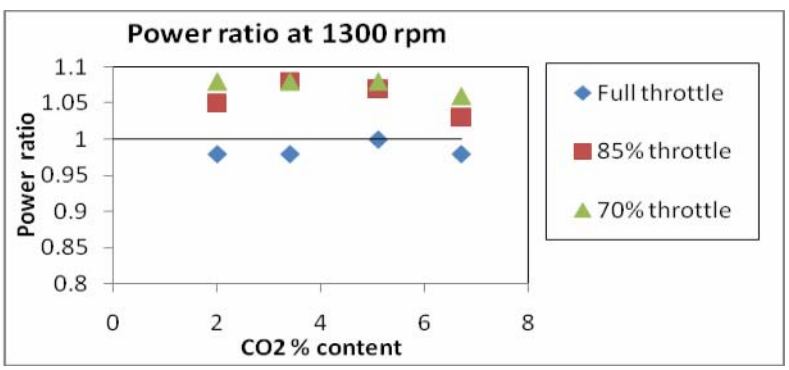

Figure 3: Power ratio comparison between pure diesel and various CO_2 concentrations

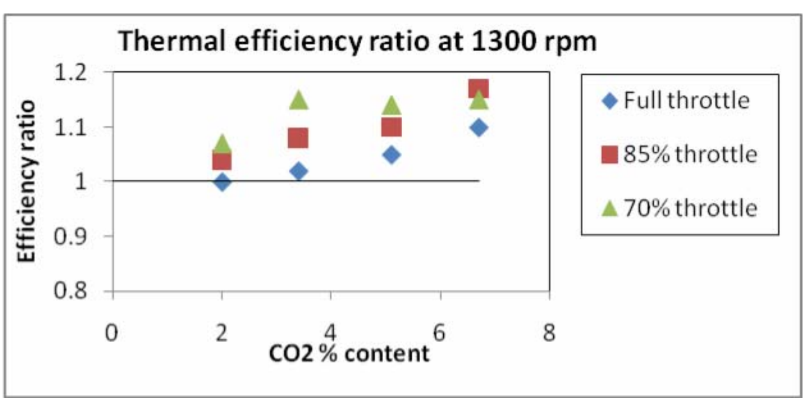

Figure 4: Brake thermal efficiency ratio for pure diesel and various CO_2 concentrations

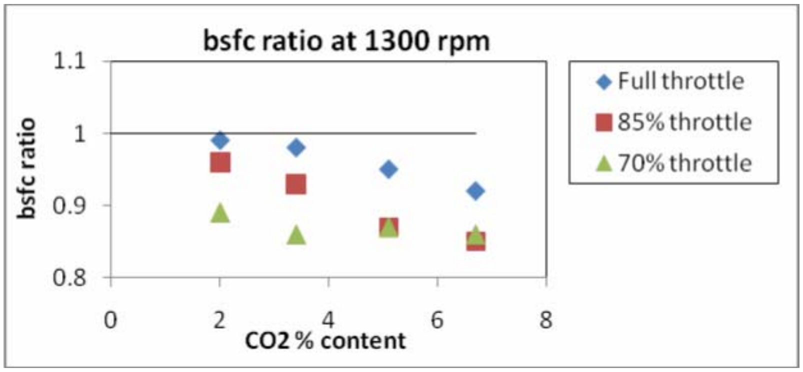

Figure 5: Bsfc ratio comparison between pure diesel and various CO_2 concentrations

Effect of CO_2 Content on Emissions.

It is well known that NO_x formation depends on the flame temperature of the combustion inside the combustion chamber; the thermal effect of CO_2 content in diesel fuel has a great influence on NO_x reduction. The pure diesel combustion registered the maximum NO_x levels for all trials of different throttles and speeds. At 85% throttle, the maximum percent NO_x reduction was 55% while the average decrease was 38%. A similar result of 57% NO_x reduction at 0.8 CO_2 mole fraction was achieved by Senda et al.[6]. NO_x results are presented on figure 6.

Smoke levels percentages were compared for the 3 throttle levels as shown in figure 7. It is clear that the maximum smoke percentages were always at the maximum torque for all throttles; the 85% throttle registered the maximum smoke level decrease which was 36% at 6.7 CO_2 content, while the average decrease in smoke level registered more than 14%. It was also clear that the smoke level is decreasing with the increase of CO_2 content; this is due to the atomization and chemical effects that were explained before.

The reduction of CO_2 concentration in products with its enrichment to diesel prior to injection into the diesel engine is worth noting. For all the throttles and concentrations CO_2 content in products was reduced, as shown in figure 8. This is due to its dissociation and reaction with soot in the combustion chamber as was explained before. The maximum CO_2 reduction in exhaust gases was 31% at 1100 rpm, 85% throttle and 5.1% CO_2 concentration.

HC emissions are formed due to inhomogenity of mixing of fuel with air during the atomization process, if the mixture is leaner than the lean combustion limit ($\phi_L \sim 0.3$). There are two major causes of HC emissions in diesel engines under normal operating conditions. The first one happens when the fuel is mixed to leaner than the lean combustion limit during the delay period, while the other is the under mixing of fuel which leaves the fuel injector nozzle at low velocity, late in the combustion process. In our case although HC emissions are relatively low with pure diesel, it was generally lowered by using CO_2. In some specific points it remains constant or slightly increased, but for the most cases it was reduced with the CO_2 mixture fuel. This could be referred to Boudouard reaction($C+CO_2=2CO$) and the better atomization and mixing of the fuel with air, these results are presented in figure 9.

CO levels in diesel engine is usually very low compared to spark ignition engines. This is due to the lean mixture that diesel engine is working on. In our case, when working at pure diesel, CO levels don't exceed 0.1%. Introducing CO_2 into the diesel before combustion is supposed to increase CO levels, this is due to the dissociation of CO_2 to CO and O. Referring to figure 10. CO levels are kept around the values of pure diesel and don't exceed 0.1% in the exhaust gases.

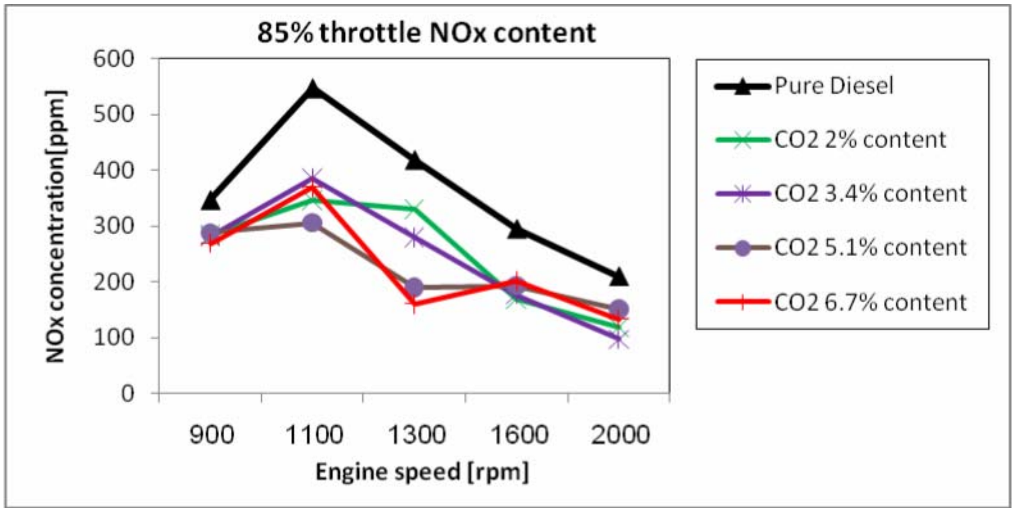

Figure 6: Effect of CO_2 content on NO_x production

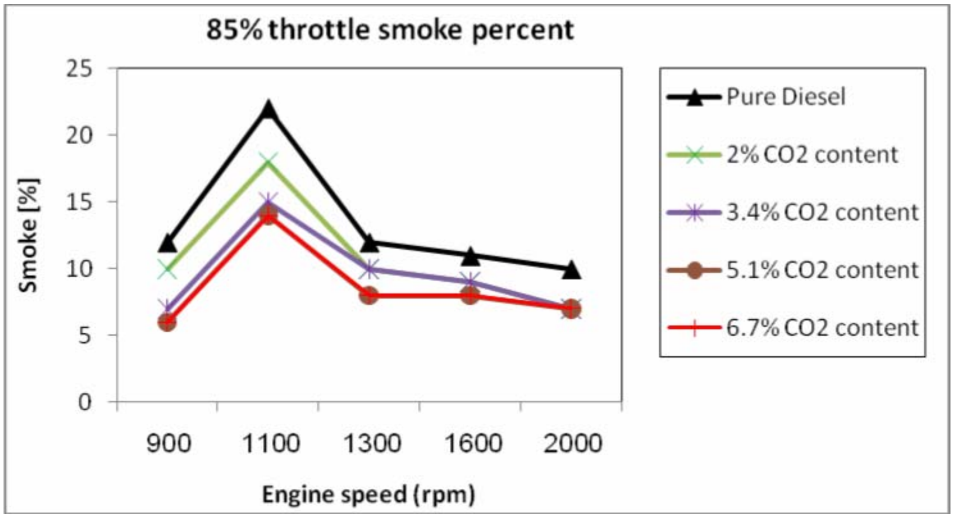

Figure 7: Effect of CO_2 concentration on smoke levels

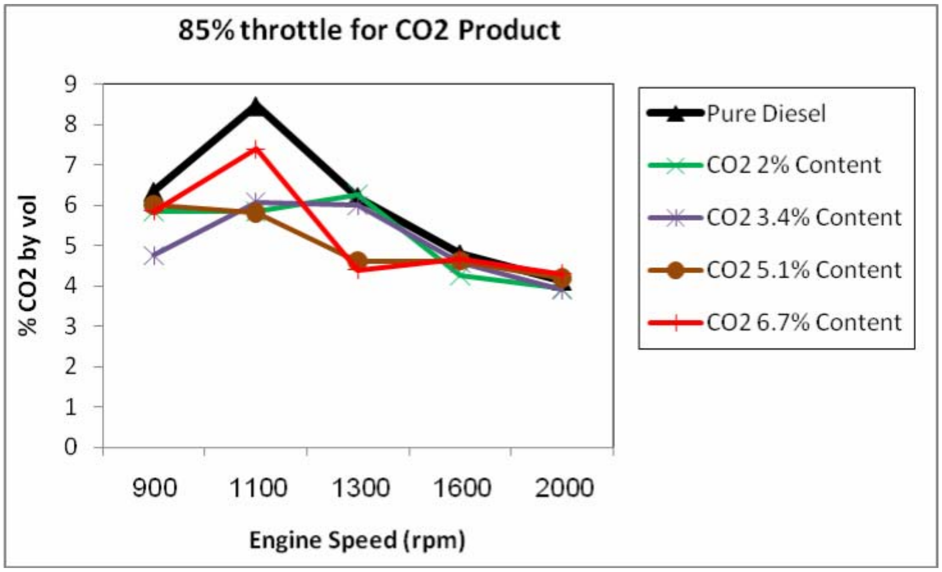

Figure 8: Effect of CO_2 content in diesel on the CO_2 in exhaust products

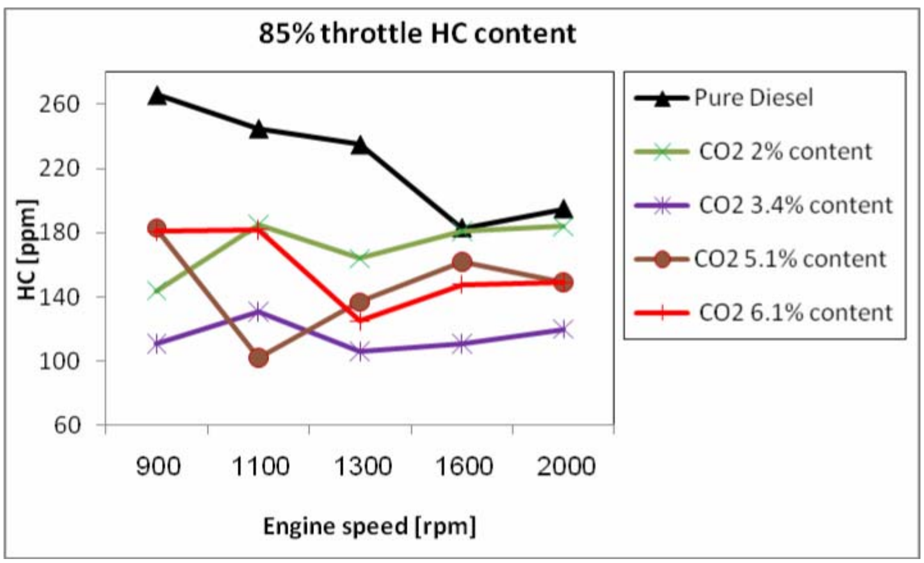

Figure 9: Effect of CO_2 content on HC in the exhaust products

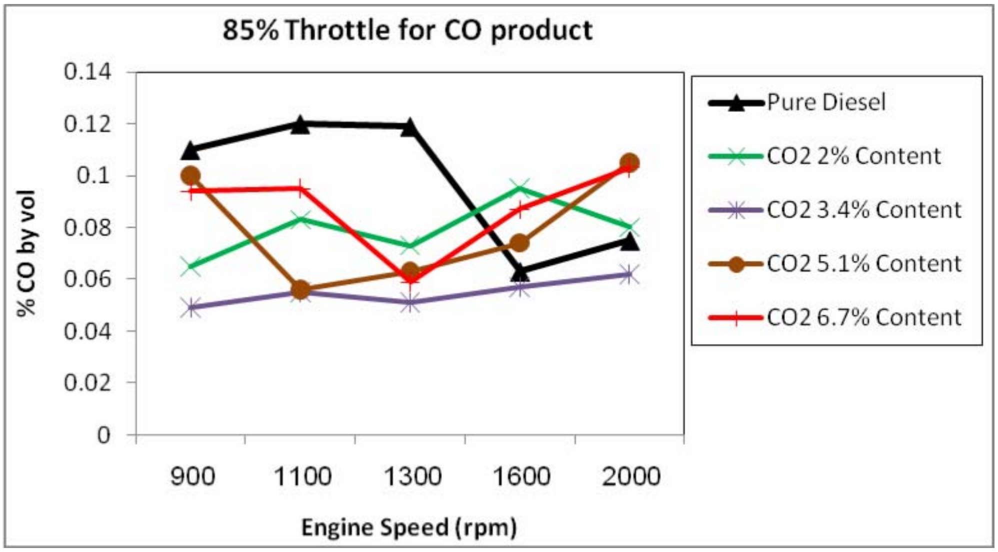

Figure 10: Effect of CO_2 content on CO in products.

Conclusion

Introducing enriched diesel with CO_2 into a real diesel engine leads to the following conclusion:

1- Torque, power and bsfc was improved up to 16%;

2- Thermal efficiency was improved up to 18%,

3- NO_x was reduced up to 54%, soot was reduction up to 36%, CO_2 in products up to 31%, and HC reduction up to 60%;

4- CO in products is kept to the lower levels; and

Finally, decreasing atomized fuel droplet size by enriching fuel with dissolved CO_2 gas was achieved, and it may help engine designers to keep injection pressure in a moderate mode, or enables larger injector nozzle diameters without increasing soot and NO_x formation. Also keeping high injection pressure and small nozzle diameter may help in decreasing soot and NO_x formation.

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