Impact of Water Injection System on Diesel Engine Brake Power and Exhaust Emissions

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ABSTRACT

A series of experiments were carried out to study and clarify the effect of Water Injection system (**WI**) on diesel engine performance and exhaust gas emissions (Nitrogen Oxides, Sulfur Dioxide, and Carbon Monoxide). The results obtained showed that, water injection increases the power output of the engine. Adding water to the incoming air allows for greater charge density. The water absorbs a large amount of heat as it vaporizes, thus reducing peak temperature and Nitrogen Oxides (NO_X) emissions. WI also decreases the emissions of Sulfur Dioxide (SO_2); the presence of water converts some of SO_2 gas into sulfuric acid (H_2SO_4). Similarly, WI system was found to decrease the emissions of Carbon Monoxide (CO).

Nomenclatures:

bp	Brake power	NO_X	Nitrogen oxides
CO	Carbon Monoxide	SO_2	Sulfur Dioxide
CO_2	Carbon Dioxide	T	Torque
ICE	Internal Combustion Engine	TC	Turbocharged Engine
WI	Water Injection		

INTRODUCTION

1- Background:

International efforts are focused on the reduction of gas emissions that contribute to global warming and atmospheric pollution. Internal Combustion (IC) engine is responsible for a portion of this pollution contributing to environmental degradation (ISO, 2002). Exhaust from diesel engines includes air pollution in the form of nitrogen oxides, carbon oxides, unburned hydrocarbons and particulate matters. These have been proven to have a negative impact on health and the environment. Increasingly, these sources are being targeted for reduction (Jahnke, 2000). Modifications to engines can effectively reduce NO_X emissions. Many manufacturers are altering engine designs to meet worldwide regulatory requirements for low NO_X emissions. However, when simple engine modifications cannot provide the necessary reductions, more extensive NO_X emissions reduction technologies are used. Some of the more common methods include Exhaust Gas Re-circulation (EGR), Direct Water Injection (DWI), fuel-water emulsions and Selective Catalytic Reduction (SCR) (Johnson, 2008).

Water injection has been used in turbine aircraft engines during World War II in order to increase takeoff power. Water injection is a method for cooling the combustion chambers of the engines by adding injected water to the incoming air, allowing for greater compression ratios and largely eliminating the problem of knocking. This effectively increases the octane rating of the fuel, meaning that performance gains can be obtained. An additional effect comes later during combustion when the water absorbs large amounts of heat as it vaporizes, reducing peak temperature and resultant NO_X formation (reducing the combustion temperature), and reducing the amount of heat energy absorbed into the cylinder walls (Wilson, 2011; Radloff**,** 2004). At a high combustion temperature the nitrogen oxides (NO_X) are formed, which react in the atmosphere to produce acids**.** Acid rain is rain or any other form of precipitation that is unusually acidic. It has harmful effects on plants, aquatic animals, and infrastructures. Acid rain is mostly caused by human emissions of sulfur and nitrogen compounds (Stern, *et al.*, 2004). Since the Industrial Revolution, emissions of sulfur dioxide and nitrogen oxides to the atmosphere have increased**.** In recent years, many governments have introduced laws to reduce these emissions**.** So the internal combustion engine causes about 49% of total gas emissions on earth (Zheng, *et al.*, 2004). Factors that affect nitrogen oxides emissions are availability of oxygen and high temperatures, if one of these factors is not present, nitrogen oxides will not be formed (Agarwal, *et al.*, 2006). It is very important to look for and find some techniques to help in reducing the quantity of engine emissions.

2- Objectives:

The aim of this study is to investigate the impact of water injection system on engine brake power, and exhaust gas emissions (NO_X, SO_2, and CO).

MATERIALS AND METHODS

All the experimental work was carried out and performed at the laboratories of Sudan University of Science and Technology. The equipments used were an IC diesel engine, dynamometer, high pressure water injection pump, and portable flue gas analyzer.

1- The Dynamometer:

Figure (1), shows the details of the experimental set-up. The hydraulic dynamometer type (HPA-Test) was used in this research. An engine type (4D56) was mounted on the test bench of the dynamometer and connected to the hydraulic dynamometerwith a propeller shaft. Dynamometer consists of an absorption unit, and usually includes a means for measuring torque and rotational speed. An absorption unit consists of some type of rotor in housing. The rotor is coupled to the IC engine. Some means are provided to develop a hydraulic braking torque between dynamometer's rotor and housing. The hydraulic dynamometer consists of a hydraulic pump, a fluid reservoir and piping between the two parts. An adjustable valve was inserted through the piping, between the water pump and the adjustable valve is a gauge or other means of measuring the hydraulic pressure. Water is added until the engine is held at a steady speed (rpm) against the load. Water is then kept at that level and replaced by constant draining and refilling, which is needed to carry away the heat created by absorbing the engine power.

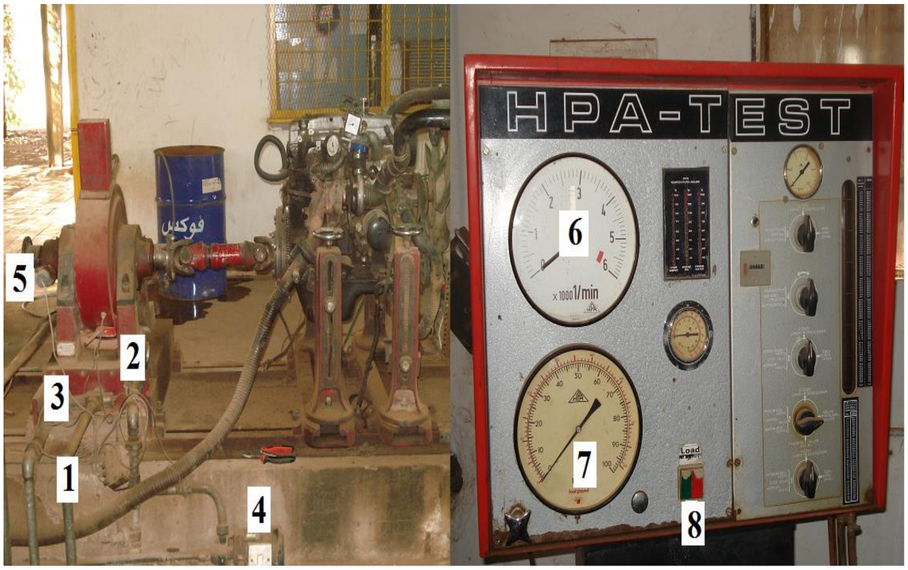


Fig. (1): Experimental set - up. 1-Water pipes. 2 - Water pressure gauge. 3 - Adjustable valve. 4 - Water pump. 5 - Speed sensor. 6- Speed gauge. 7 - Torque gauge. 8 - On – Off load.

The housing attempt to rotate in response to the torque produced but is restrained by the scale or torque metering cells that measure the engine speed and torque.

2- Portable Flue Gas Analyzer:

This research aims to study the effect of water injection on exhaust gas emissions. To achieve these goals, a portable flue gas analyzer was used. Eurotron portable flue gas analyzer type GreenLine 8000 was used. It consists of two units, **M**ain **C**ontrol **U**nit (**MCU**) and the **R**emote **C**ontrol **U**nit (**RCU**). The MCU is a portable flue gas laboratory, and the RCU is used to display the measured data. Figure (2), shows the main components of the portable gas analyzer MCU and RCU. The flue gas is sucked into the analyzer through a probe by a primary pump; the sample is cleaned up and dried by a dust filter and condensation trap. The toxic gases (CO, SO_2, NO, and NO_2) are measured by means of an electrochemical unit. The gas sensors are electrochemical cells composed of two electrodes (anode and cathode) and an electrolyte solution, depending on whether the gas has to be detected or not. The sampled gas goes through selective diffusion membranes. The oxidation process produces an electrical signal output proportional to the gas concentration. This signal is evaluated by electronic device, converted to digital, processed by the microprocessor, sent to RCU displayed, eventually printed, with a resolution depending on the sensor (Internet, 2011).

Fig. (2): The Main components of flue gas analyzer. 1- Exhaust pipe. 2- Metal hole. 3- Steel tube and handle. 4- RCU power supply. 5- Communication cable. 6- Gas suction hose. 7- MCU power supply.

3- Water Injection System:

Figure (3), shows the arrangement of water injection pump, which was built locally to satisfy the needs of experimental tests. Initially the pump of water injection is adopted to provide water at pressure (5 and 10 bar) with nozzle diameter (0.1, 0.3, and 0.5 mm). The location of the nozzle has been selected to be through the intake manifold before the turbocharger, the nozzle is to be far enough away from the engine inlet, the injected water has more time to atomize and mix with the air. Practical calculations have been carried out to determine the mass flow rate of water injection for each nozzle at the pressure (5 and 10 bar), and are sorted in Table (1).

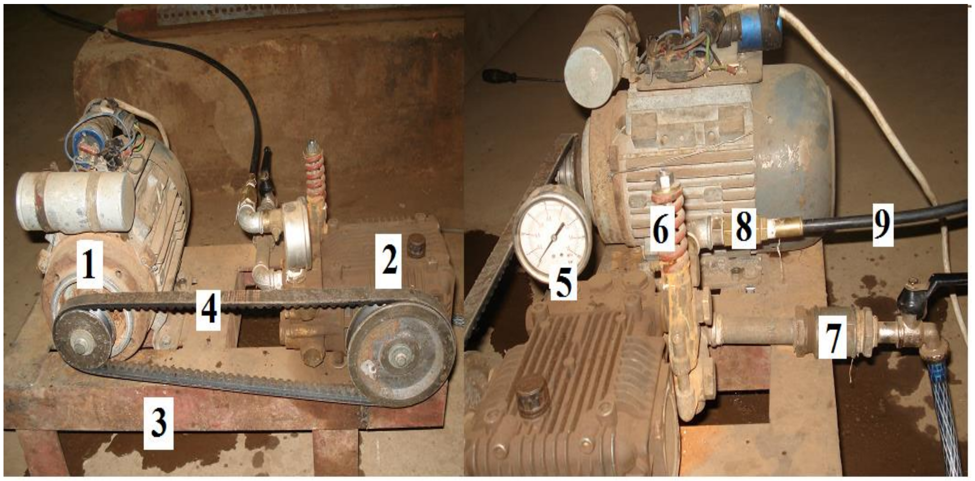


Fig. (3): Water injection pump. 1- Motor drive. 2- High pressure water pump. 3- Metal seat. 4- V – belt. 5- Pressure gauge. 6- Adjustable valve. 7- Water inlet. 8 – Water outlet. 9- High pressure hose.

Table (1): Mass flow rate of Water Injection system

Nozzle Diameter (mm)	**Pressure**	**Mass flow rate (kg/s)**	**Pressure**	**Mass flow rate (kg/s)**
0.1	**5bar**	1.367e-4	**10bar**	2.2e-4
0.3		7.283e-4		9.2e-4
0.5		1.236e-3		1.52e-3

4- Tests Procedure:

First the Turbo Changed (TC) engine will be run without injected water with four different speeds 1000, 1500, 2000, and 2500rpm (4 experiments), the objective of running the engine without water injection is to create a reference to study the effect of WI on engine performance and exhaust emissions. Second the TC engine will be operated with water injection systems, at which the engine runs (4 different speeds) by each water injection rate (Table 1) 24 experiments. The brake power will be calculated when measuring the engine speed (rpm) and torque (Nm) by dynamometer (see Fig 1). The exhaust emissions (NO_X, SO_2, and CO) have been measured by using the gas analyzer (Fig 2). All data required to conduct this study are obtained by experiments and are shown in Table (2).

Table (2): Experimental Results

Engine Condition	N (rpm)	Torque (N-m)	B. Power (kW)	NO_X (ppm)	CO (ppm)	SO_2 (ppm)
TC Engine	1000	55	5.758	165	18	30
	1500	75	11.778	136	52	102
	2000	85	17.798	111	80	153
	2500	90	23.554	105	92	193
TC + WI (0.1mm at 5bar)	1000	40	4.188	92	29	12
	1500	85	13.347	85	47	89
	2000	95	19.898	68	70	94
	2500	100	26.173	60	78	84
TC + WI (0.1mm at 10bar)	1000	37	3.888	86	24	10
	1500	87	13.617	81	43	83
	2000	97	20.208	65	66	88
	2500	102	26.803	57	73	75
TC + WI (0.3mm at 5bar)	1000	31	3.239	80	22	9
	1500	90	14.127	77	40	77
	2000	100	20.848	62	60	80
	2500	104	27.303	54	65	68
TC + WI (0.3mm at 10bar)	1000	28	2.969	75	20	7
	1500	66	10.378	73	37	71
	2000	85	17.798	57	54	74
	2500	95	24.863	50	57	58
TC + WI (0.5mm at 5bar)	1000	25	2.619	70	17	6
	1500	59	9.268	69	35	61
	2000	72	15.169	53	48	66
	2500	79	20.734	45	52	50
TC + WI (0.5mm at 10bar)	1000	15	1.569	65	16	4
	1500	56	8.778	65	33	55
	2000	70	14.749	49	45	62
	2500	77	20.155	40	47	44

RESULTS AND DISCUSSIONS

1- Brake Power:

Referring to Table (2) and Figure (4), water injection increased the engine brake power at mid and high engine speeds. For example the brake power of TC engine setup and at 2500rpm was 23.554kW, and at engine set-up TC+WI (0.1mm at 5bar) the power was equal to 26.173kW, the increment ratio about 10% when compared to TC engine.

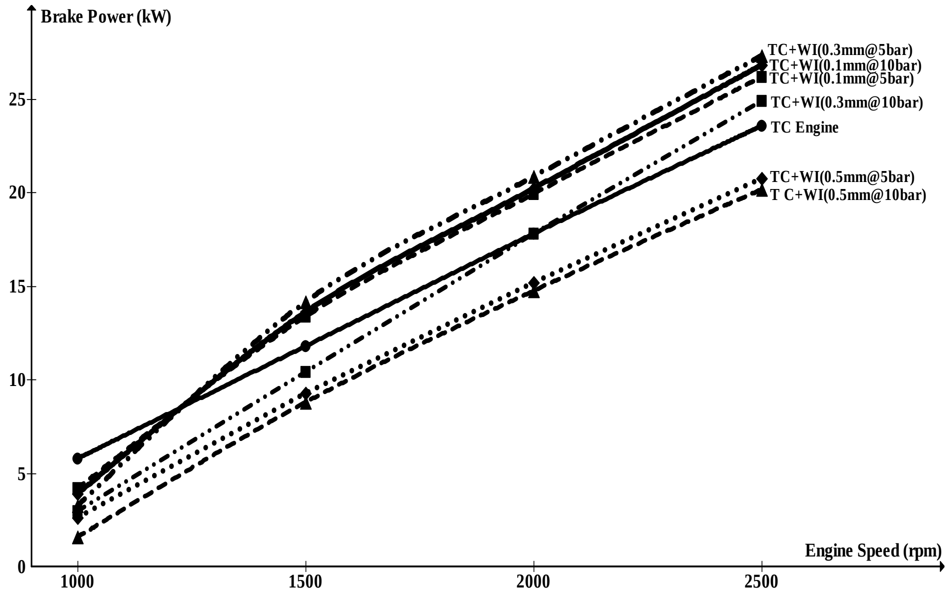


Fig (4): The effect of W I system on engine brake power.

The maximum power can be obtained when using set-up TC+WI (0.3mm at 5bar) and was equal to 27.303kW about 13.7% greater than that obtained by TC engine setup. Water injection greater than that acquired by setup (0.3mm at 5bar), caused a decrease in engine power when compared to TC engine setup. At test setup TC+WI (0.5mm at 5bar) the power decreased to 20.734kW. The brake power decreased to 20.155kW in the case of more water injection by using setup WI (0.5mm at 10bar). The losses of power when compared to the power of the TC engine are 11.9% and 14.4% respectively. The reason of increase in power is attributed to the injection of water to the incoming air, which tends to cool the combustion chambers of the engine, allowing for greater compression ratios. At low engine speeds less than 1250 rpm approximately, the brake power was reduced and reached values less than that obtained by TC engine. The charged air by TC engine at low engine speeds are less compared to the high speeds, and hence the least rate of injected water (0.1mm at 5bar) is considered as much for the air at low engine speeds. For example the power of TC engine at 1000rpm was found to be 5.758kW, in the presence of water by setups 0.1 mm at 5bar, 0.3mm at 5bar, and 0.5mm at 10bar, the power deceased to 4.188 kW, 3.239kW and 1.569kW respectively. The reduction ratios are 27.3, 43.7 and 72.8% respectively when compared to TC engine setup.

2- Nitrogen Oxides:

Table (2) and figure (5), show the impact of the WI system with different rates of injected water on NO_X emissions. From Fig (5) it is clear that as WI increases the NO_X emissions decreases. The NO_X formation depends on the peak temperature, and since the injected water reduces the peak temperature then the NO_X emissions will decrease. For example at TC engine setup and 2000rpm the reading of NO_X emissions is 111ppm. When WI system is set to 0.1mm at 5bar, the NO_X emission reduced to 68ppm. If more water is added by using setup 0.1mm at 10bar, the NO_X reading was equal to 65ppm. The NO_X reduction will decrease continuously as the rate of injected water increases, the reduction percentages of NO_X are 38.7% and 41% respectively when compared to the NO_X emissions of TC engine. The maximum reduction in NO_X obtained by the maximum rate of injected water (0.5mm at 10bar), at which the NO_X emissions are equal to 49 ppm about 60% reductions when compared to TC engine emissions.

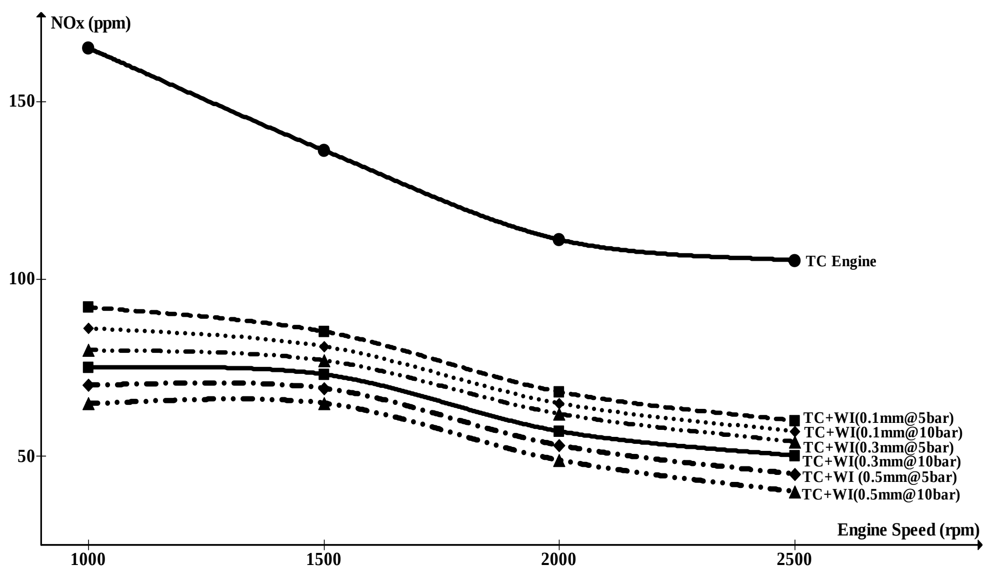
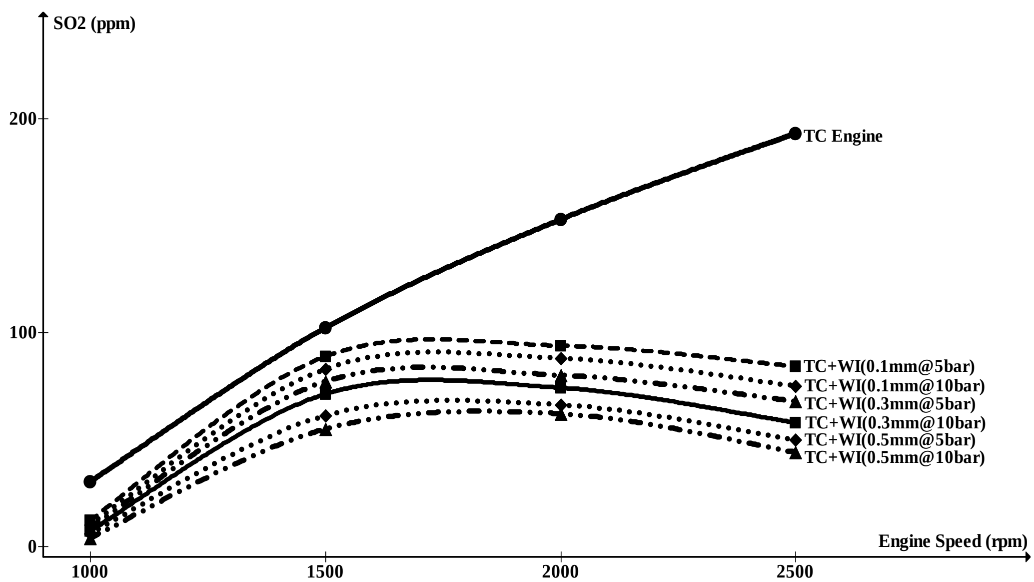


Fig (5): The effect of WI system on NO_X emissions.

3- Sulfur Dioxide:

Figure (6) shows that the emissions of SO_2 decreased significantly, at all engine speeds and as the rate of injected water increases, the emissions of SO_2 decreased. For example at TC engine and 2000rpm the SO_2 emissions was 153ppm. When the water injected by the setup (0.1mm at 5bar), the SO_2 emission reduced to 94ppm. More reduction in SO_2 emission was obtained by increasing the rate of injected water. At test setup TC+WI 0.5mm at 5bar the SO_2 was equal to 66ppm, the reduction ratios are 38.5 and 56.8% when compared to emissions of TC engine. Because of the presence of a specific percentage of sulfur elements in fuel, so the low amount of SO_2 emitted from exhaust does not mean that the water injection treats the existence of the sulfur in fuel, but the injected water changed the sulfur dioxide into sulfuric acid. Sulfur dioxide (SO_2) is created during the combustion process from small amount of sulfur present in fuel. During certain conditions the catalyst oxidizes sulfur dioxide to make SO_3, which then reacts with water to make Sulfuric Acid (H_2SO_4), which is very corrosive to combustion chamber parts.



The effect of WI system on (SO_2) emissions. Fig (6):

4- Carbon Monoxides:

Figure (7), shows the effect of WI rates on CO emissions. As the rate of injected water increases, the formation of carbon monoxide decreases. The graph shows that, all the values of CO emitted from engine due to addition of injected water are less than that obtained by set-up of TC engine at mid and high engine speeds, also the CO will increase as the engine speed increases. For example at 2500rpm and TC engine setup, the CO emissions was found to be 92ppm, at water injection setup 0.1mm at 5bar, the CO decreased to 78ppm. More water by setup 0.3mm at 5bar the reading of CO is 65ppm, at maximum rate of injected water (0.5mm at 10bar) the CO lowered to 47ppm, the reduction percentages are 15.2, 29.3, 48.9% respectively when compared to TC engine emissions.

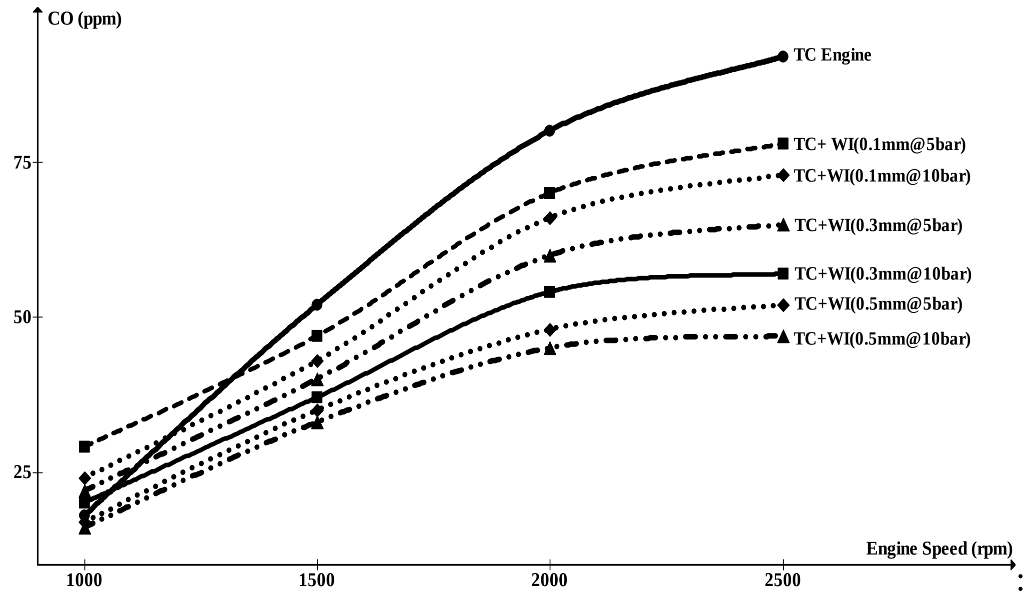


Fig (7) The effect of WI systems on (CO) emissions.

Carbon monoxide is produced from the partial oxidation of carbon-containing compounds. Carbon monoxide will form when there is not enough oxygen to produce carbon dioxide (CO_2). While water injection will cool the incoming air significantly, which increase its density and hence the amount of air that enters the cylinder. This is an explanation of why carbon monoxide reduced when adding injected water to the incoming air; and this might be attributable to the water-gas shift reaction, in which CO and H_2O shift to form CO_2 and H_2. The water-gas shift reaction (WGS) is a chemical reaction in which carbon monoxide reacts with water vapor to form carbon dioxide and hydrogen.

CONCLUSIONS

Water Injection system is found to cause the power to raise, while the emission of NO_X was reduced significantly. Also the impact of WI is positive in reducing the emissions of carbon monoxide. Since the amount of sulfur content in the fuel is constant, WI will make some of sulfur to dissolve in water to form sulfuric acid (H_2SO_4), and hence the net result is a reduction in sulfur dioxide. The most critical effect of sulfuric acid on engine parts is the abrasion of interior surfaces of the internal combustion engine such as cylinder liner, piston, piston ring, cylinder head and engine valve.

REFERENCES

Agarwal, D. S. Sinha, A. K. Agarwal, (2006). "Experimental investigation of control of NOx emissions in biodiesel – fueled compression ignition engine". Renewable Energy, Vol. 31, 2006, pp 235.

International Organization for Standardization (ISO) (2002). Reciprocating Internal Combustion Engines - Exhaust Emission Measurement, Part 4: Test Cycles for Different Engine Applications, ISO 8178-4, First Edition, pp 3.

Internet (2011). http://www.eurotron.com/eurotron_uk/dettaglio_prodotto.aspx?ID=25&IdProdotto=64.

Jahnke, J. A. (2000). "Continuous Emission Monitoring". Second Edition. John Wiley & Sons, Inc. New York, NY.

Johnson, T. V. (2008). "Diesel emission control technology in review". SAE 2008-01-0069. Warrendale, Pa.: SAE, pp5.

Radloff, E., (2004). "Water Injection System for Emissions Reduction Tested on MV Cabot: Test Plan and Test Results, TP 14272E, Transportation Development Centre, Transport Canada, Government of Canada, June 2004.

Stern, C., R. Boubel, D. Turner, and D. Fox. (2004). "Fundamentals of Air Pollution". Orlando, Fla.: Academic Press, pp59

Wilson, J. Parley. (2011). "Effects of Water Injection and Increased Compression Ratio in a Gasoline Spark Ignition Engine. Wilson, Thesis, University of Idaho, pp106.

Zheng, M. G. T. Reader, J. G. Hawley, (2004). "Diesel engines exhaust gas recirculation a review on advanced and novel concepts". Energy Conversion Management. Vol.45, 2004, pp 883.

الملخص

نُفذ تحقيق تجريبي لدراسة وتوضيح أثر حقن الماء على أداء محرك الديزل من حيث القدرة الفرملية و إنبعاث غازات العادم (اكاسيد النيتروجين، ثاني اكسيد الكبريت، واول اكسيد الكربون). النتائج أوضحت أن نظام حقن الماء يزيد القدرة الخارجة من المحرك، إضافة الماء الى الهواء المسحوب يؤدي لزيادة كثافته. نظام حقن الماء يلعب دوراً هاماً في خفض إنبعاث غازات اكاسيد النيتروجين من محركات الديزل بصورة ملحوظة، نتيجة لامتصاص الماء كميات كبيرة من الحرارة عند تبخره، مما يؤدي الى خفض درجة حرارة جدار اسطوانة الحريق. نظام حقن الماء يخفض من إنبعاث غاز ثاني اكسيد الكبريت، الماء يلعب دوراً في تحويل جزءاً من غاز ثاني اكسيد الكبريت الى حامض الكبريتيك. غاز اول اكسيد الكربون ينخفض مع نظام حقن الماء حيث تنخفض كمية الغاز المنبعثة.