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The effect of tap water emulsified fuel on exhaust emission of single cylinder compression ignition engine

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Abstract. An experimental investigation on exhaust emissions with emulsion fuel was conducted in a diesel engine that equipped with a "Real Time Non-Surfactant Emulsion Fuel Supply System, RTES" under four different loads operations (1, 2, 3 and 4 kW). RTES is a mixing device that able to produces non-surfactant emulsion fuel which is one of the alternative ways to improve the exhaust emissions of diesel engine, especially Nitrogen Oxides (NOx) and Particulate Matter (PM). As for the test fuel, neat diesel (D2) and tap water-in-diesel emulsion fuel (W/D) are tested as a comparison. Based on the experimental results, emulsion fuel decrease NOx radically compare to D2 in all load conditions with an average reduction of 18.99% respectively. As for the PM, emulsion fuel is lower compare to D2 at all load conditions and lowest at high load. However, tap water emulsion fuel shows high formation of Carbon Monoxide (CO) at all load conditions which due to lower combustion temperature. This significant increment is aligned with the reduction of NOx emissions.

1 Introduction

Nowadays, greenhouse gasses in our atmosphere have been increasing. Over 90% of the causes of the climate change come from human activities [1] of which the biggest cause of this catastrophe is contributed from tmospheric emission. The largest growth in this emission has come from industry and transportation [2]. Diesel engine, due to better power economy, power performances and durability are widely applied in mass transportation, heavy industries machinery and agricultural sectors. In spite of their preferable superiority, diesel engines are suffering from harmful exhaust emissions especially particulate matters, PM and nitrogen oxides, NOx [3]. These emissions are not only harmful to the environment but also hazardous to human's health, but they also lead to a serious damage to the health like lung cancer, asthma, cardiovascular issues and other fatal illness that would cause

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death. However, introduction of water into diesel engine has been figured out by the researcher to simultaneously reduce the formation of NOx and PM emissions.

Water-in-Diesel (W/D) emulsion fuel is the promising alternative fuel that meets the requirement of emission regulations hence become a potential alternative fuel that could contribute the world's needs. There are several emulsification methods that have been introduced by researchers all over the world. For example, A. Kulchitskiy and A. Attia [4] used membrane emulsification and investigated the effect of emulsion fuel structure to the diesel engine. Moreover, Yilmaz et. al [5] also has prepared emulsion fuel with different method by using auxiliary emulsifier mono ethylene glycol, tested it in a turbocharged diesel engine and analyzed the emissions characteristics. However recently, there is a mechanical approach to produce emulsion fuel and the main objective of this concept is to continuously emulsified diesel and water without the presence of surfactant before instantaneously supplied to the engine. This new emulsification concept has been introduced by A.M. Ithnin et. al [6] which known as Real-Time Non-Surfactant Emulsion Fuel Supply System (RTES). As for this research, the purpose is to investigate the exhaust emissions which are NOx, PM and Carbon Monoxide (CO) of diesel engine fuelled with different types of fuel which one of that is W/D emulsion fuel that emulsified by using RTES. Tap water has been selected as water source to produce the W/D emulsion fuel.

1.1 Emulsion fuel

W/D emulsion fuel is the promising alternative fuel that meets the requirement of emission regulations hence become a potential alternative fuel that could contribute the world's needs. Moreover, it does not require any modification of the engine. The water-in-diesel emulsion fuel type is preferable to be the alternative fuel compared to the other emulsion fuel is because of high difference in boiling point between water and diesel fuel. Term emulsion is defined as a mixture of two or more immiscible liquids [7] which are unblended in nature. It is formed with the help of mechanical agitation together with the chemical additives so called surfactant that attract both the unblended liquids in forming one stable solution. The presence of surfactant is to form a stable emulsion that important in order to ensure this alternative fuel run accordingly in the engine. In W/D, there is a special phenomenon that only happened during emulsion fuel combustion called as micro-explosion phenomenon (figure 1). Ivanov and Nevedov reported that W/D experienced a spontaneous explosion during the combustion [8], hence caused the smaller fuel particles to be in contact easily with the air for complete combustion and reduces the generation of PM, NOx, CO and other pollution materials without decrease the combustion efficiency [9].

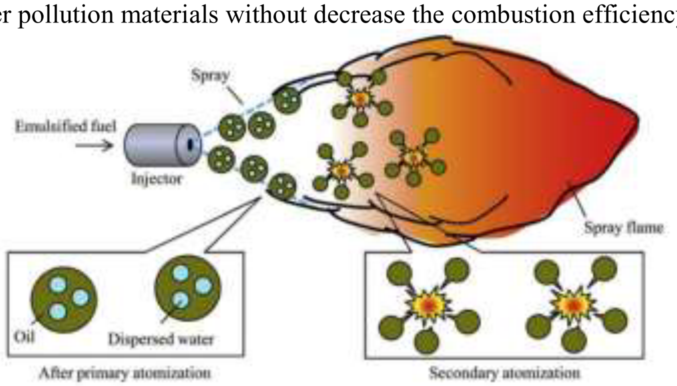

Fig. 1. Diagram of the occurrence of micro-explosion process [10].

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1.2 Diesel fuel

Vehicle emission standard (Euro standard) is emission standard constructed specifically for vehicles and it is categorized based on the formation of Nitrogen Oxides (NO_x), Hydrocarbon (HC), Particulate Matter (PM) and Carbon Monoxide (CO) in vehicle exhaust emissions. Fuel quality is also required alongside Euro stages. In order to achieve air quality requirements that significantly reduce Sulfur (S), it is necessary for vehicles to use Euro 3 and above within other parameters such as Benzene (C_6H_6) and olefins or aromatics, which able to significantly reduce [11]. Low grade diesel fuel was widely used in non-developing countries and also in some developing nations [12]. Fuel quality contains very high Sulfur (S), Lead (Pb), Benzene (C_6H_6) and olefins or aromatics causing severe damage to the environment and also to the diesel engine. Table 1 shows the details of low grade diesel fuel specifications, which is Euro 2 standard (D2).

Table 1. D2 diesel fuel specification [13].

Specifications	**D2**
Calorific value, MJ/kg	45.280
Cloud point, °C	18
Density, kg/L, 15 °C	0.8538
Total Sulfur, mass %	0.28
Viscosity, cSt, 40 °C	4.642
Distillation temperature, 90% recovery, °C	367.9
Flash Point, °C	93.0
Pour Point, °C	12
Cetane number	54.6
Carbon (C), wt %	84.1
Hydrogen (H_2), wt %	12.8
Sulfur (S), wt %	0.2
Nitrogen (N), wt %	0.1
Oxygen (O_2), wt %	3.9

1.3 Tap water

In Malaysia, water supply management and development is not centralized. It is managed by state governments. The State Water Authorities or private companies will supply tap water from treatment plant to residential areas. This tap water comes from surface water like lakes, reservoirs and streams and groundwater. The latest tap water quality criteria and frequency of monitoring were given by Engineering Service Division (ESD), Ministry of Health Malaysia. Quality of tap water is monitored by ESD at least four times in a year collected in shops, school and university and housing area. Tap water samples were analyzed by NovAA 400 Flame Atomic Spectrophotometer (AAS) system to evaluate chemical element [14]. Chemical element percentage in tap water is shown in Figure 2. Main chemical elements are Chloride (Cl), Sulphate (SO_4) and Natrium (Na). Metal element in chemical characteristics such as Magnesium (Mg), Iron (Fe) and Zinc (Zn) present in tap water due to the corrosion of plumbing material. Once tap water is treated, it must travel along pipes and become contaminated with metal elements when it flows from treatment plant to consumer.

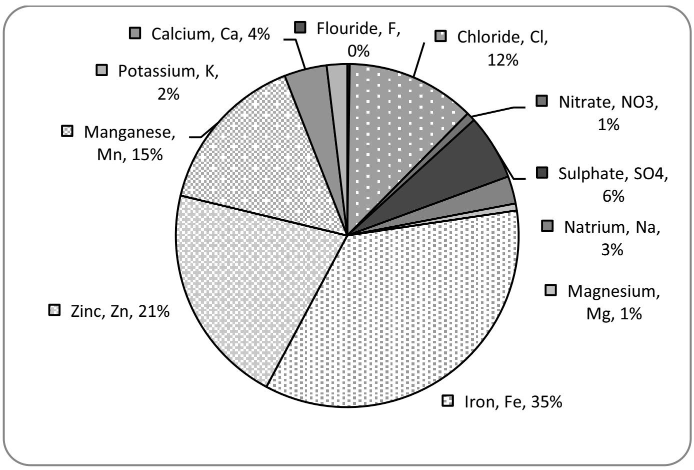

Fig. 2. Distribution of chemical element percentage bonding in tap water [14].

1.4 Real Time Non-Surfactant Emulsion Fuel Supply System (RTES)

RTES is a mechanical approach to produce emulsion fuel and the main objective of this concept is to continuously emulsified diesel and water without the presence of surfactant before instantaneously supplied to the engine [6]. RTES is a high potential concept because of its ability to remove the dependency of surfactant without affecting the benefits of emulsion fuel. On the market, there are variance types of surfactant available and the price is quite expensive. Due to that, the alternative fuels are much more expensive and not cost effective compare to the neat diesel fuel since they require a high amount of emulsifier and other chemical additives. Figure 4 shows the process flow of RTES.

2 Experimental setup

For the purpose of this experiment, two types of fuel have been tested which are neat diesel Euro 2 (D2) and tap water emulsion fuel (W/D tap water). W/D tap water emulsion fuel has been emulsified by using RTES. The experiment was performed under four different loads which are 1kW, 2kW, 3kW and 4kW by using an electric generator which has a direct injection diesel engine, single cylinder, 4-stroke and air-cooled. The detailed specifications of the engine are listed in table 2.

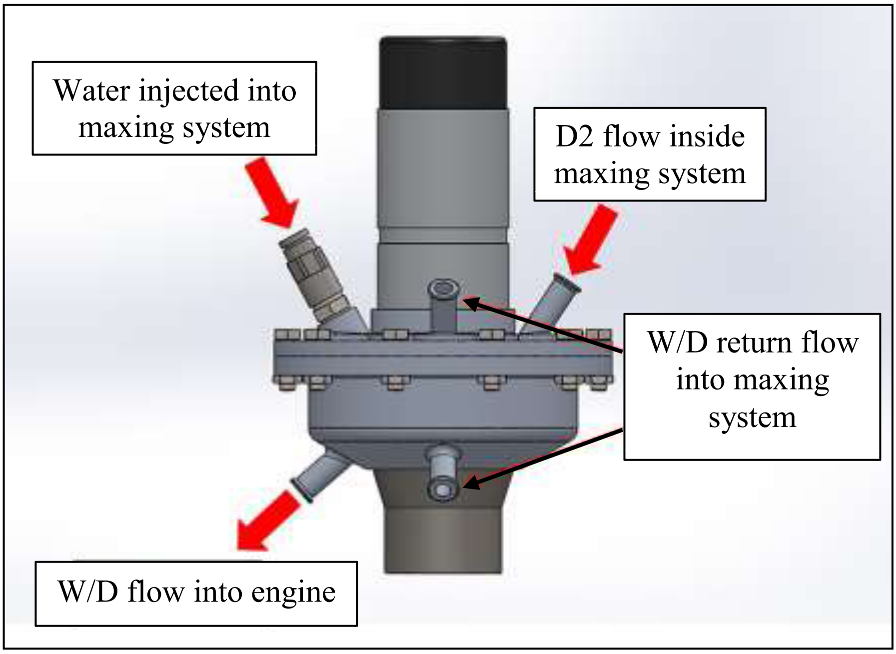

Fig. 4. Process flow of RTES [6].

Table 2. Diesel engine specification.

Parameter	**Specification**
Engine Type	4-stroke, single cylinder, direct injection
Cooling System	air cooling
Bore x Stroke (mm)	86 x 70
Displacement Volume (l)	0.406
Compression Ratio	19.3
Maximum Power (kW)	5
Fuel Injection Timing (bTDC)	13
Fuel Injection Pressure (MPa)	19.6
Rated Revolution (rpm)	3750

Diesel engine testing has been carried out in Low Carbon, Vehicle System Engineering laboratory, MJIIT UTM. Figure 5 shows the schematic diagram of engine test setup.

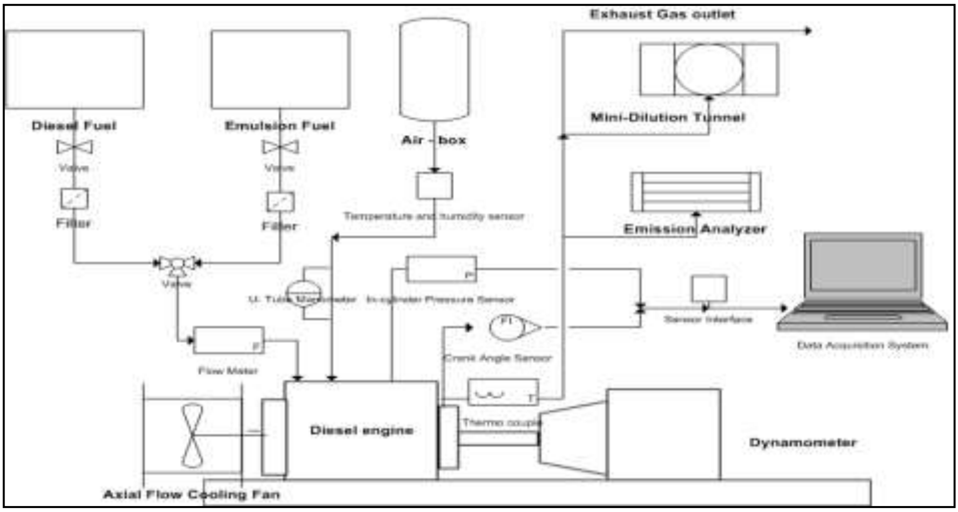

Fig. 5. Schematic diagram of diesel engine test bed setup.

As for emission measurement, two measurement instruments have been used in this experiment which is emission analyzer to measurement the emission of NO_x and CO and a mini dilution tunnel to measure the PM. Emission analyzer used in this test is Testo 350. During testing, probe of the analyzer was placed inside the exhaust of the engine and data has been transferred into the data logger. Figure 6 shows Testo 350 Emission Analyzer. Measurement is recorded every 5 seconds interval during 2 minute duration of engine running.

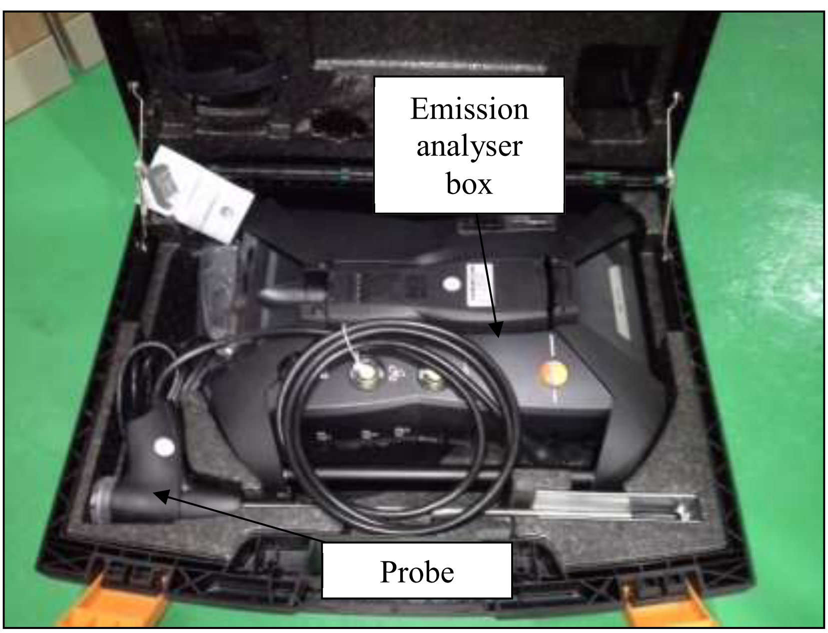

Fig. 6. Testo 350 Emission Analyser.

Schematic diagram and photo of mini dilution tunnel to measure PM is shown in Figure 7. Exhaust smoke from engine flow through main tunnel. Distribution of exhaust smoke is sucked into dilution tunnel by dilution pump, together with heated clean air. Temperature of clean air is maintained to 50 °C that heated by heater. Air filter is used to filter impurities in air before it enters tunnel. Ratio of exhaust gasses that is diluted into dilution tunnel is set to 10:1. This can be done by measuring CO_2 concentration from main tunnel and also in dilution tunnel. If the ratio of CO_2 does not reach 10, speed of dilution pump is increased until it matches required value. The device used to measure CO_2 is Cambridge Sensotec Rrapidox 3100 dual gas analyser. It uses infrared (IR) sensor technology to detect the CO_2 measurement and has high accuracy with sensor range of 0 to 5000 ppm. When dilution ratio matches with value of 10, diaphragm pump is switched on to transfer diluted exhaust smoke through PM filter.

Filter used for trapping the PM is Teflon filter (Millipore FHLP04700) with diameter and orifice of 47 mm and 0.45 μm respectively. Gas meter is used to measure the volume of smoke through PM filter. The gas meter used is Shinagawa W-NK wet gas meter. Volume of absorbed gasses is set to 100 L in every filter. PM formation is determined by weighing PM filter before and after experiment. Filter is stored into a closed container equipped with silica gel for 12 hours. This is to absorb the moisture on the filter that may affect the measurement. The weighting device used is Quartz Crystal Microbalance Mettler AE240 with accuracy of 0.00001 g.

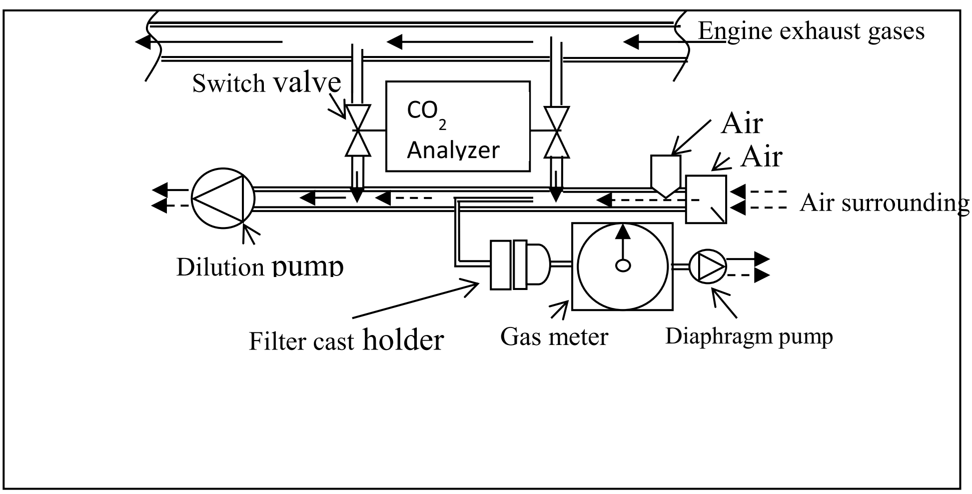

Fig. 7. Schematic diagram of mini-dilution tunnel.

3 Results and discussion

3.1 Nitrogen Oxides (NO_x)

Nitrogen Oxides (NO_x) emission for emulsion fuel under different engine load conditions compared with D2 is shown in Figure 8. It shows that W/D tap water emulsion fuel reduce NO_x significantly compared with D2 in all load condition. Average reduction NO_x per load for W/D tap water is 18.99%. In diesel engine, the creation of NOx is related to the accessibility of oxygen and high combustion chamber temperature. Consequently, this explained the reduction of NOx when using emulsion fuel. With emulsion fuel, the water existence reduced the peak temperature because of high latent heat from water vaporization that absorbs the heat during combustion. Besides, the increment in OH (hydroxyl) radicals which would react with excess oxygen also affects the reduction of NOx formation [15].

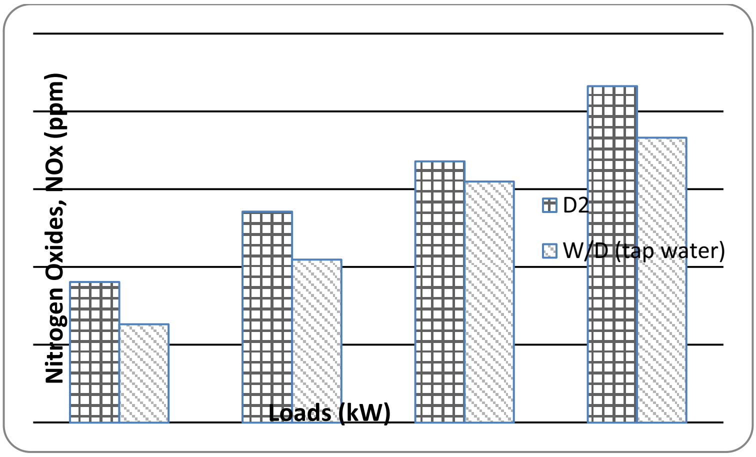

Fig. 8. NO_x emissions for W/D tap water emulsion fuel compared with D2 under different loads condition.

3.2 Particulate Matter (PM)

Particulate Matter (PM) for W/D tap water emulsion fuel under different engine load conditions compared with D2 is shown in Figure 9. Comparing with D2, emulsion fuel shows lower PM at all loads condition. The reduction of PM with the usage of emulsion fuel is due to the increase of OH radical with the addition of water during the combustion in the combustion chamber which leads to the oxidation of soot precursors. Besides, J.M.Ballester relates that PM reduction with improved combustion efficiency due to better air-fuel mixing process that produces micro-explosion phenomena. Micro-explosion occurs at secondary atomization of initial spray with rapid water evaporation process that is contained in droplet, tearing up droplet into very fine particles, thus helping to improve combustion [16].

3.3 Carbon Monoxide (CO)

Carbon Monoxide (CO) emissions for W/D tap water emulsion fuel under different engine load conditions compared with D2 is shown in Figure 10. W/D tap water emulsion fuel shows high formation of CO at initial load compare to D2. In general, lower combustion temperature of emulsion fuel yields higher CO emissions than conventional diesel fuel. Because of the presence of water, there is no sufficient temperature to convert CO to CO_2 [17]. K.A.Subramanian explained when temperature is lower than 1400 K, the oxidation process of CO will freeze [18]. However at high load, CO formation starts to reduce and becomes closer with D2 due to micro-explosion process at secondary atomization that explodes droplet into very fine droplets, thus improving air-fuel mixing process.

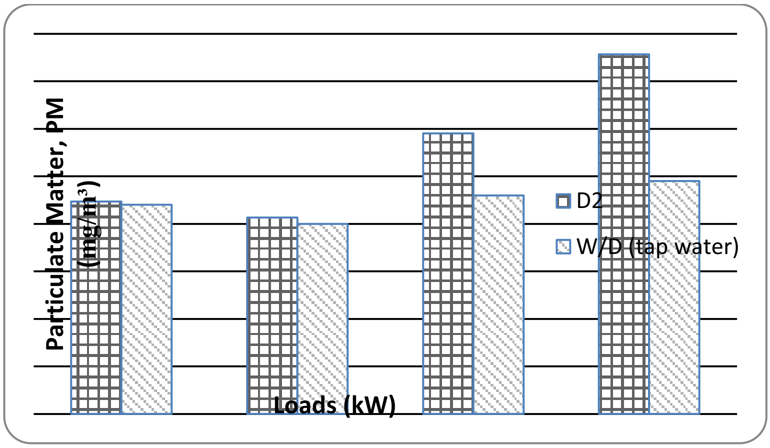

Fig. 9. PM for W/D tap water emulsion fuel compared with D2 under different loads conditions.

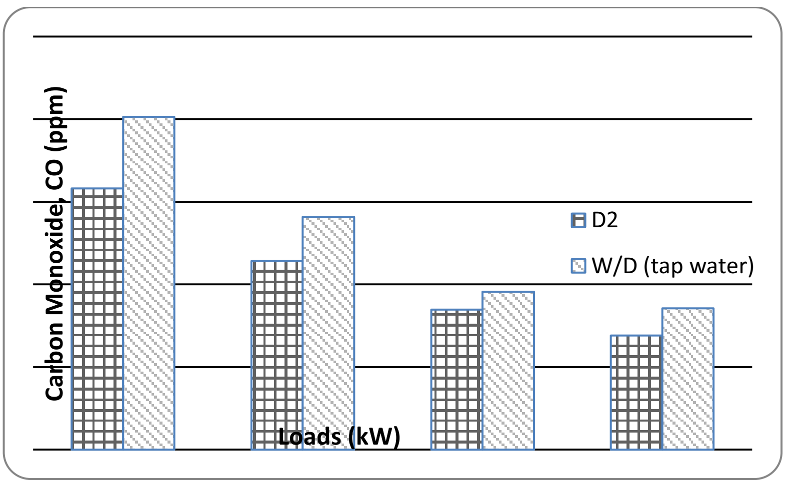

Fig. 10. CO emission for W/D tap water emulsion fuel compared with D2 under different loads conditions.

4 Conclusions

From this study, it is concluded that W/D tap water emulsion fuel gives better emissions compare to neat diesel fuel. As for NOx, average reduction when compared to D2 for W/D tap water emulsion fuel is 18.99%. Moreover, at all load conditions, W/D tap water emulsion fuel produce lower PM and the highest reduction was recorded at 3 kW and 4 kW. Lastly, for CO, due to lower combustion temperature, W/D tap water emulsion fuel shows high formation of CO at all load conditions compare to D2.

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