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Performance, Combustion Characteristics, and Emissions of Compression Ignition Engine Operated with Fusel Oil –Diesel Blend

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Nomenclature

ISFC	Indicted specific fuel consumption
ITE	Brake thermal efficiency
F10	90% gasoline + 10% fusel oil d by volume
F20	80% gasoline + 20% fusel oil by volume
IMEP	Indicted mean effect pressure
LHV	Low heating value
NOx	Nitrogen oxide
CO	Carbon monoxide
CO2	Carbon dioxide

ABSTRACT

Biofuels from Biomass are meant to decrease significantly dependence on fossil oil and reduce the environmental influences on energy use. Fusel oil one of biofuel that composed of a mixture of alcohols. Fusel oil by-product obtained during fermentation of agricultural products such as beet, cone, sweet molasses, grains, potatoes. Fusel oil can be used as a clean and high-efficiency compression Ignition fuel with a reduced NOx. The energy value of fusel oil is near to other alternative combustible types. The primary objective of this study was to determine performance, combustion characteristics and emissions of a single cylinder diesel engine operated with fusel oil-diesel blend. The experimental study was performed at constant engine speed, 17.7 compression ratio and various engine loads (0%, 25%, 50% and 75%). The engine power, torque, indicated specific fuel consumptions, maximum in-cylinder pressure, ignition delay and emissions (carbon monoxide CO, carbon dioxide CO_2, and nitrogen oxide NO_x) determined. The engine torque and power of fusel oil - diesel blend slightly decreased compared with pure diesel. However, important changings were not observed on the maximum in-cylinder pressures. The ignition delay of diesel was shorter than of F20 by 5% at all engine loads. Furthermore, the increment in indicated specific fuel consumption (ISFC) happened with F20, especially at 75% engine load. Furthermore, the reduction in nitrogen oxide NO_x emissions occurred at all engine loads. While the carbon dioxide (CO) and carbon monoxide (CO_2) emissions are increased. **Conclusion:** The high-water-content, low cetane number and heating value of F20 represent the reason of the adverse effect on engine performance**.**

INTRODUCTION

At present times, the world energy usage has grown significantly due to the effect of industrialization. This includes the using of oil products, natural gaseous, electricity, coal, as well as and renewable energy such as alternative fuels. Also, the research on alternative renewable fuels has become quite important worldwide due to anxieties about the impacts of conventional fuel usage on global warming (Demirbas, 2005). Alternative fuels

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can be obtained from the renewable material such as waste agriculture and can offer decrease of conventional fuel consumption. Alcohol fuels produced from renewable resources, those including higher than two carbon atoms, have been proposed as blend components in diesel to decrease in mineral fuel consumption and emissions. The most common fuels that are conceded under alcohols are ethanol, methanol, and butanol (Demirbas, 2008).

Compression ignition engines are widely preferred compared to spark ignition engines. This is due to their undoubted advantages of fuel consumption and power output. Besides, CO, CO_2 and HC emissions produced in diesel engines are significantly less than of SI engines (Brijesh and Sreedhara, 2013). Due the lower heating value of alcohol and oxygenated fuel has effects on the engine performance and emission of CI engine by increased the SFC and slightly decreased the power. While they have positive effects on engine emission (Ali *et al*., 2015).

The purpose of utilizing alcohols as a means of producing cleaner diesel engines was founded overhead 50 years ago, Also, there several studies achieved with alcohols as pure, blended and additive with diesel in compression-ignition (CI) engines with diesel (Kisenyi *et al*., 1994; Agarwal, 2007; Bayraktar, 2008). The significant research conducted with methanol, butanol, and ethanol–diesel blends on CI engine. Hulwan and Joshi (2011) performed their test on direct injection (DI) diesel engine and blends of ethanol, diesel, and biodiesel. As results, the brake specific fuel consumption increased considerably; thermal efficiency enhanced slightly; smoke opacity decreased especially at high loads (Hulwan and Joshi, 2011). NO_x variation released with operating conditions while carbon dioxide CO emissions dramatically increase at low loads.

Fusel oil has the appearance of an alternative fuel for use in internal combustion engine. The structure and quantity of the fusel oil depend on the kind of carbon utilized in the alcohol production, fermentation process, preparation method, and decomposition method of the fusel oil in the mixture (Calam *et al*., 2014). The utilization of fusel oil as an alternative fuel can be accepted as a new energy source in diesel engines. However, the study of using fusel oil with diesel very a few in literature also there are limited studies achieved with gasoline in spark ignition engine. Awad *et al*. (2016) used 20 percentage of fusel oil with diesel in single cylinder CI engine. They were achieved study at different engine speeds and load. As a result in the engine power and the torque with fusel oil–diesel blends slightly decreased compared to those with diesel. Furthermore, the indicated specific fuel consumption (ISFC) was slightly increased, particularly at 75% engine load during high engine speeds, while the ignition delay for F20 had been longer by 7% at all engine loads and speeds compared to those with diesel. Furthermore, a decreasing in NO_x emissions was seen at all engine loads and speeds and the highest decreasing in NO_x for fusel oil -diesel was 28% with 1500 rpm at both loads. Also, it was found that both CO_2 and CO emissions increased. However, high water content, low cetane number, and low heating value of fusel oil were the reasons for the adverse effect displayed upon the performance of the engine. The high water content of fusel oil (10-20%) ceased adverse effect on engine combustion and contributes to decreasing the heating value of fusel oil (Solmaz, 2015; Demirbas, 2002). Solmaz (2015) reported that the engine torque slightly reduced when fusel oil used.While the engine torque was reduced averagely to 6% and 2% respectively when F100 and F50 fuel were used (Solmaz, 2015). found the power and torque of comparison ignition engine with F20 (20% fusel oil -80% diesel) slightly dropped compared to pure diesel while the fuel consumption increased (Awad *et al*., 2016).

The main objective of this study was to determine performance and emissions of a single cylinder diesel engine operated with fusel oil -diesel blend at 2100 rpm and different engine loads. The study performed at constant engine speed, 17.7 compression ratio and various engine loads (0%, 25%, 50% and 75%). The engine power, torque, indicated specific fuel consumptions maximum cylinder pressure, ignition delay and emissions (carbon monoxide CO, carbon dioxide CO_2, and nitrogen oxide NO_x) determined.

Methodology:

Experimental set-up:

The test engine was a 0.63L YANMAR TF120M single cylinder compression ignition engine. The specifications and the engine diagram of this test are shown in Table 2 and Fig. 1. The data were recorded by the TFX Engineering DAQ system, which consisted of the in-cylinder pressure sensor, and crank angle sensor. Next, the ambient temperature and the exhaust gas temperature, which were measured by using K-type thermocouples, were collected by Pico thermocouple data logger. Besides, the thermocouples were placed at air measurement unit and exhaust manifold, while the emissions were measured by using Kane auto 4-1 series exhaust gas analyzers. The experiments were conducted with four engine loads at 0%, 25%, 50% and 75%. The tests have been carried out with diesel F0 and fuel oil-diesel blend F20 (20% vol. fusel oil and 80% vol. diesel). Fusel oil contains approximately 13.5% of water content. Also, its lower heating value is less than that of diesel. The tests were carried out under steady state conditions and first started with pure diesel to obtain the base data of the engine. The engine power, the engine torque, the indicated specific fuel consumption (ISFC), the exhaust temperature, and the emissions (CO_2, CO, and NO_x) were measured via experiments as well.

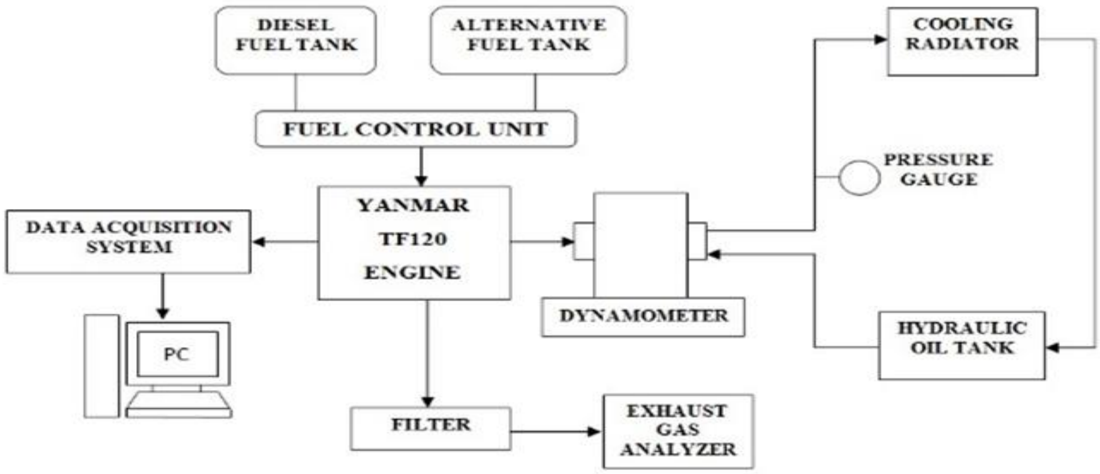

Fig. 1: *YANMAR TF120 engine diagram*

Table 1: Engine specification

Description	Specification
Engine model	YANMAR TF120
Engine type	diesel 4 stroke, single engine
Bore x Stroke (mm)	92 x 96
Displacement (L)	0.638
Injection timing	17° BTDC
Compression ratio	17.7
Continuous output (HP)	10.5 HP at 2400 RPM
Rated output (HP)	12 HP at 2400 RPM

Test fuels:

Diesel (F0) and fusel oil-diesel (F20) blends were used in the tests. The fuels used in the tests were placed at room temperature for 48 hours and no phase change was detected. The fuel properties (density, heating value, moisture content, and boiling) for fusel oil and F20 diesel were measured in the chemical laboratories of University Malaysia Pahang (UMP) according to ASTM standards. The higher heating value (HHV) of the fuel samples is determined according to ASTM D 240, using oxygen bomb calorimeter Model 6772 (Parr Instrument company, USA). The density of the fuel samples is measured at 15°C according to ASTM D 4052 using density /specific gravity meter, model DA-640. The dynamic viscosity of the fuel samples was determined according to the ASTM 445-01 fuel standards by using a Brookfield DV-II+ programmable viscometer. The oxygen, carbon, hydrogen, and sulphur were measured by Intertek laboratories in Kuala Lumper –Malaysia. The carbon, hydrogen, nitrogen and sulphur according to ASTM D5291, ASTM D5291, ASTM D5291 and ASTM D1552 respectively. Meanwhile, the cetane number of pure diesel was taken from (Yasin *et al*., 2014) and all properties of the fuel tests are shown in Table 2.

Table 2: Physical properties

Fuel properties	Diesel	Fusel oil	F20
Density [kg/m^3]	746	847	761
Higher heating value KJ /kg	47.5	29.53	42.12
Cetane Number	46	-	-
Moisture content %	-	13.5	0.88
Boling point [°C]	-	98	201
H (%)	33–16	5.749	-
C (%)	84-87	21.658	-
N (%)	0	0.326	-

RESULTS AND DISCUSSION

The performance, combustion characteristics, and emission of compression ignition engine are directly affected by the type of fuel. As mentioned in section 2.1, the study tests were attained with single cylinder CI engine using pure diesel F0 (100 %vol diesel) and F20 (80%vol diesel and 20%vol fusel oil). The indicated power, indicted torques, indicated specific fuel consumptions, in-cylinder temperature, in-cylinder pressure, ignition delay and engine emissions (CO), (CO_2), (NO_x) emissions were measured. Fig. 2 illustrates the engine power at 2100 rpm engine speed and different engine loads (0%, 25%, 50% and 75%) for all tested fuels. It can be observed that the engine power increased with increasing engine loads. Also, it was seen the engine power of fusel -oil diesel blend (F20) slightly lower than pure diesel at all engine load. Furthermore, Fig 3 was shown the torque increased with increasing the engine loads for all test fuels, and the higher torque was with diesel. Despite the low heating value of fusel oil–diesel blend proportion to diesel, it has seen that the power and torque have slightly decreased with pure diesel (F0). The similar results of reduced power and torque were achieved by using fusel oil–diesel (Awad *et al*. 2017), biodiesel-diesel (Xue, Grift, and Hansen 2011; Murillo *et al*. 2007) and ethanol-diesel blends (Abu-Qudais, Haddad, and Qudaisat 2000). The oxygen content of fusel oil represents one of the main reason to improve the in-cylinder combustion reactions, while the higher water content (13.5%) of fusel oil considered one of the reasons that lead to worse combustion and increased the heat loss through cylinder wall due to the longer combustion duration. Thereby, as a result, the power and torque decreased. The maximum engine power and torques have measured 75% load

Fig. 2 illustrates the maximum in-cylinder pressure of F20 and pure diesel at 2100 rpm engine speed and a different engine. Almost the maximum in-cylinder pressure of diesel slightly higher than F20 at all engine loads. Due to the higher water content and the lower heating value of fusel oil, the pressure dropped with F20 comparison with diesel that affected negatively on engine power and torque (Calam *et al*., 2014). However, significant changings were not seen on the maximum in-cylinder pressures.

Specific fuel consumption SFC is based on the torque produced by the engine on the fuel mass flow given to the engine. Measuring SFC based on the in-cylinder pressures (the ability of the pressure to do work) is indicated specific fuel consumption [ISFC]. Through the engine loads increases, the fuel driven into the cylinder also increases. The low heating value of fusel oil-diesel blend (42.12 MJ/kg) comparison to pure diesel (47.5MJ/kg) led to increasing the amount of fuel to produce the same power (Awad *et al*., 2017). Despite the low heating value of F20 proportion to diesel, it has seen that the torque and power have slightly reduced comparison with diesel. The variance of indicated specific fuel consumption of diesel and F20 at 2100 and four engine loads are illustrations in fig. 5. At all engine loads, the indicated specific fuel consumption [ISFC] of diesel lower than F20. Furthermore, the latent heat of evaporation of alcohol based fuels is higher than diesel that permits lower manifold temperatures and higher volumetric efficiency (Yücesu *et al*. 2006; Bilgin, Durgun, and Sahin 2002). The ignition delay is identified as the period between the start of injection and the start of combustion (Canakci, 2007; Hardenberg and Hase, 1979; Xing-cai *et al*., 2004).As shown in Table 3, the ignition delay was determined on the basis of crank angle (CA) between the start of injection and the start of combustion and then converted from angle to time (MS) by Eq. (1).

$$t\ (MS)=CA/(N.(min/60).(360/rev))*1000 \quad (1)$$

It was seen that the ignition delay for diesel was shorter at all engine loads comparison with F20. Furthermore, the decreasing in ignition delay of F20 could be explained by the lower latent heat of vaporization of fusel oil, lower cetane number and the higher water content fusel oil that limited the engine combustion.

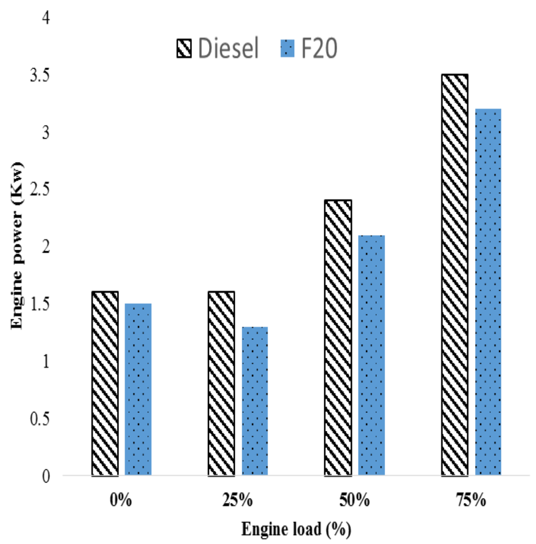

Fig. 2: *Variation of power for Diesel and F20*

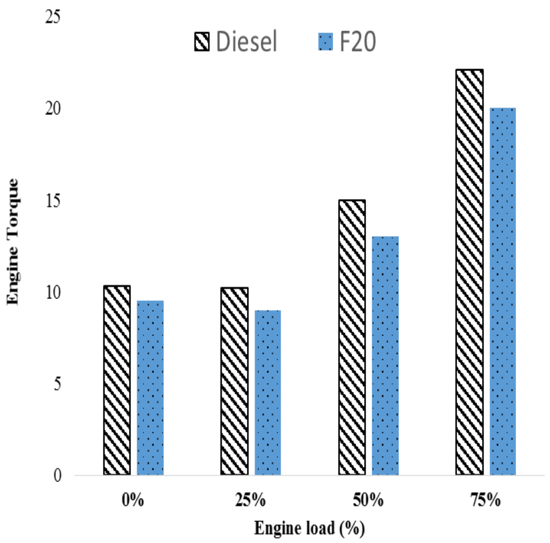

Fig. 3: *Variation torque for Diesel and F20*

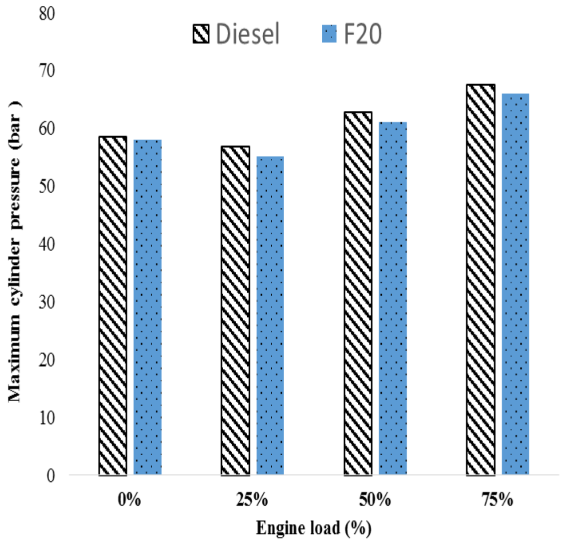

Fig. 4: *Variation MCP of diesel and F20*

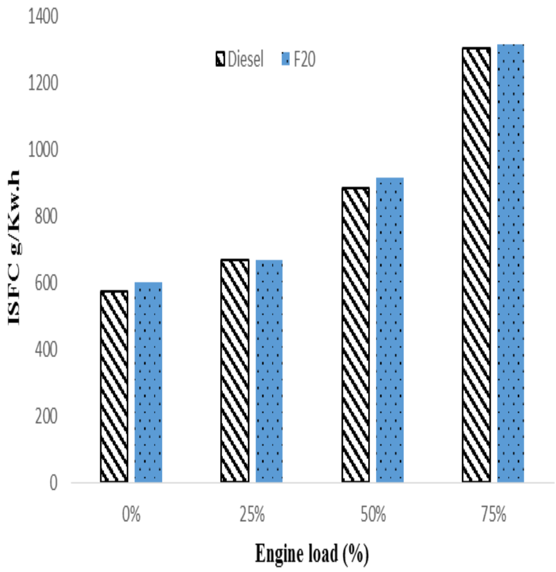

Fig. 5: *Variation ISFC of diesel and F20*

Table 3: Ignition delay of diesel and F20 at different loads

Diesel					Fusel oil –diesel blend (F20)			
load	the start of injection	Start of combustion	ignition delay (CA)	ignition delay (MS)	the start of injection	Start of combustion	ignition delay (CA)	ignition delay (MS)
0%	-17	3.73	20.73	1.645	-17	4.01	21.01	1.667
25%	-17	4.89	21.89	1.7373	-17	5.04	22.04	1.749
50%	-17	4.98	21.98	1.744	-17	5.14	22.14	1.757
75%	-17	5.08	22.08	1.752	-17	5.18	22.18	1.760

The engine emissions such NO_x, CO and CO_2 emission in compression ignition engine have an association between engine operating conditions and fuel properties that drive to increasing or decreasing emission. It is understood that NO_x emissions produced by higher combustion temperature and higher oxygen content of the fuel (Koç *et al*., 2009; Rajasekar *et al*., 2010). Alcohols usually provide lower combustion temperature due to their lower heating value and oxygen content (Agarwal, 2007). The impacts of fusel oil on emissions very related to engine operating conditions and the water content of fusel oil that ranges from (5-20%). NO_x is the greatest harmful gaseous emission from a CI engine, and it has highly related on the combustion temperature and all engine operating conditions (Chong *et al*., 2010). NO_x formation happens at temperatures above 1500°C, and the rate of the formation increases quickly with increasing temperature above 1500°C temperature(Cybulski and Moulijn, 2005). Fig. 6 illustrates the NO_x emission of F20 and diesel at the different engine. The NO_x emission increased as engine loads increased, while the NO_x of F20 at almost less than diesel. The reduction in NO_x due to the high-water content (13.5%) of fusel oil (Awad *et al*., 2017; Calam *et al*., 2015). Also, the exhaust temperature of F20 as shown in Fig. 7 was lower than diesel that effected on engine emission.

Fig. 8 illustrated the CO_2 emission of diesel and F20 at various engine loads. The CO_2 emission of F20 and diesel increased as engine loads. The CO_2 of F20 almost same with diesel except at 25% engine load. While the CO with increased F20 compared with diesel and the increment was significant as shown in Fig 9. The main reason for the increasing in the emission can explain it due to the high C/H ratio in fusel oil as shown in Table 2. Also, a high oxygen content of fusel oil leads to an increment in CO emission.

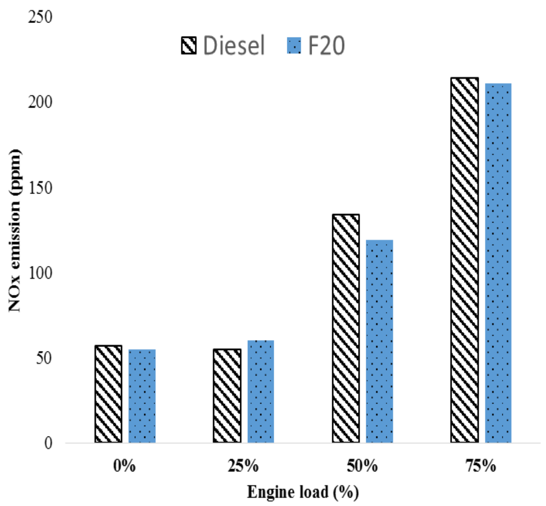

Fig. 6: *Variation NO_x emission of diesel and F20*

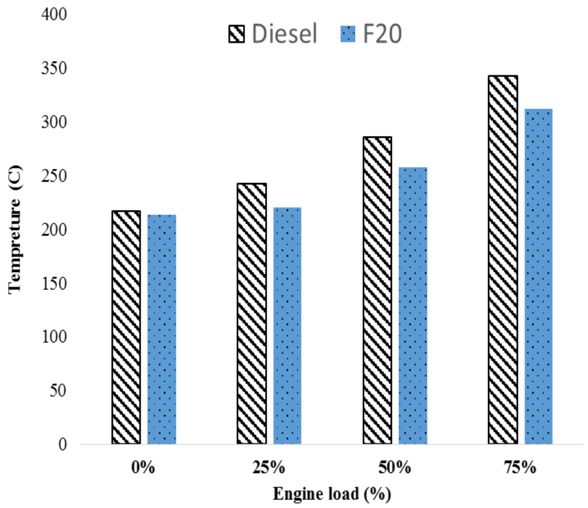

Fig. 7: *Variation exhaust temperature of diesel and F20*

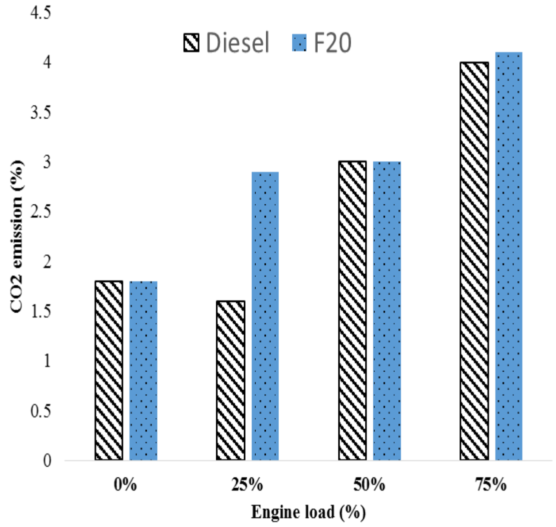

Fig. 8: *Variation CO_2 emission of diesel and F20*

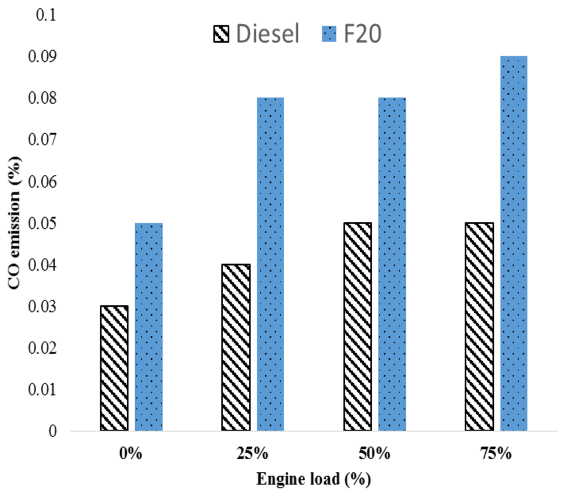

Fig. 9: *Variation CO emission of diesel and F20*

Conclusions:

Fusel oil is a by-product of alcohol production. Fusel oil consists of ethyl alcohol, methyl alcohol, isoamyl alcohol, isobutyl alcohol, and n-propyl. In this paper using pure diesel and of fusel oil –diesel blend F20 (20% fusel oil) in a compression ignition engine under 2100 rpm engine speed and four engine loads. From the discussions above, we can conclude that.

The blending fusel oil with diesel by 20% leads to increase the oxygen content of the blended fuel and water content. While the heating value reduced of thetest fuel compared with diesel. The engine torque and power for F20 slightly decreased compared with pure diesel. However, significant changings were not observed on the maximum in-cylinder pressures. The ignition delay for F20 prolonged by 5% at all engine due to the high-water content that led to prolonged combustion duration. Furthermore, the increment in indicated specific fuel consumption (ISFC) happened with F20 especially at 75% engine load. At all operating conditions, fusel oil–diesel blended (F20) the NOx emission decreased. The maximum reduction in nitrogen oxide (NO_x) happened at 25% engine load that was around 10%. The CO and CO_2 emissions with F20 were 30 % and 10 % respectively compared with pure diesel. The exhaust temperatures decreased because of the water content of fusel oil. Thus, CO and CO_2 emissions increased rapidly.

The high moisture content in fusel oil, which was at about (13.5%), and the low heating value caused negative combustion that might have restricted the flame, thereby; high heat loss was detected through the wall of engine cylinder that led to a reduction in engine thermal efficiency, besides causing negative effects upon the engine

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