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Effects of triethylene glycol mono methyl ether (TGME) as a novel oxygenated additive on emission and performance of a dual-fuel diesel engine fueled with natural gas-diesel/biodiesel

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A B S T R A C T

The need for energy sources is one of the major problems for all countries in the world. Biodiesel is one of the alternative fuels. The use of 5% biodiesel in diesel fuel blend is usual, and most countries have planned to use 20%. Glycerol is a by-product of biodiesel production. Therefore, due to the increase in this substance, glycerol management is substantial. In this study, biodiesel was produced by the transesterification process from waste cooking oil (WCO); then, the triethylene glycol mono-methyl-ether (TGME) as a novel additive obtained from glycerol by the etherification method. The Dual-Fuel Diesel Engine mode (DFM) is one of the most suitable ways of achieving efficient and clean combustion. Dual-fuel combustion has been performed through the use of natural-gas (NG) as the main fuel and diesel/biodiesel blend The DFDEm engine was run under three different high NG ratios (60, 70, and 80%), at full-load and 1500 rpm. Biodiesel was used at two levels of 5 and 20 vol%. TGME was added at four levels (0.1, 0.2, 0.3 and 0.4 vol.%) to fuel blends. Results showed that glycerol conversion and recycling into TGME additive is important, because, the presence of oxygen in the chemical structure of the TGME additive can make it a suitable oxygenated additive. The TGME as an oxygenated additive improved the most parameters of the engine. Oxygenated fuels contributed to the combustion process and improved it. The best conditions achieved by adding 0.2 vol% TGME additive into diesel fuel at the DFM engine in NG70 mode, under these conditions in comparison to conventional diesel combustion brake power, and brake thermal efficiency increased by 10.54 and 12.77%, but the generated power cost amount decreased by 20.16%. Also CO, CO_2, and NOx emissions decreased by 76.77, 40.9, 1.31%, respectively.

1. Introduction

Nowadays, the need for new energy sources is one of the major problems of all countries in the world. Fossil fuel consumption generally increased by about 51% between 1995 and 2015. This consumption has been predicted to increase by approximately 18% between 2015 and 2035 (Yildiz, 2018). Annual global energy demand is more than 12 billion tons of petroleum fuel (BTOE), which leads to the release of 39.5 Gt-CO_2, and if more energy is required, it will also increase the annual CO_2 emissions to 75 Gt-CO_2 in the future. The upward trend in fossil fuel consumption increases CO_2 and greenhouse gas emissions (GHG), which is the leading cause of global warming and endangers the health of the human race and the environment. Engine exhaust gas emissions by fossil fuel consumption cause changes in climatic conditions (Braungardt et al., 2019). Ozone is formed when the engine's exhaust gases (hydrocarbons and nitrogen oxides) are exposed to sunlight. At normal levels, greenhouse gases retain some of the sun's heat in the atmosphere and help warm the earth (Day and Day, 2017). With increasing fossil fuel consumption, ozone formation increases, leading to the formation of a layer called the ozone layer in the atmosphere, which leads to heat imbalance, which causes global warming, acid rain, and environmental and health damage. Replacing energy with low-carbon fuels is necessary to solve the climate change problem (Abas et al., 2015). Using a combination of alternative fuels (biodiesel, natural gas, and ethanol, etc.) to improve fuel

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Nomenclature

TGME	Triethylene glycol mono-methyl-ether
NG	Natural-Gas
SFM	Single-Fuel Engine mode (Diesel)
DFM	Dual-Fuel Engine mode (Diesel + NG)
B5	5 vol% Biodiesel + 95 vol% Diesel
B20	20 vol% Biodiesel + 80 vol% Diesel
GRP	Glycerol Reduction Process
GEP	Glycerol Etherification Process
WCO	Waste Cooking Oil
EGT	Exhaust Gas Temperature
CA	Crank Angle
φ	Equivalence Coefficient
A/F	Air/Fuel
HRR	Heat Release Rate
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
P_{fuel}	Fuel Power
BTE	Brake Thermal Efficiency
GPC	Generated Power Cost
LHV	Low Heat Value
CO_2	Carbon dioxide
CO	Carbon monoxide
NOx	Nitrogen oxides
GHG	Greenhouse Gas Emission
IEA	International Energy Agency

combustion, improve engine performance and reduce the use of fossil fuels can be good solutions (Shamun et al., 2018). Research in the commercial and industrial sectors is conducted to improve engine performance, increasing energy efficiency, and reducing emissions (Dimitrakopoulos et al., 2019). Among fossil fuels, natural gas (NG) is more environmentally friendly (Wang et al., 2019). The use of NG in a Dual-Fuel Diesel Engine (DFM) is more efficient when used a more uniform mixture of NG and air in combustion (You et al., 2020a). DFM engine (by replacing part of diesel fuel with NG fuel) is one of the most suitable ways for achieving efficient and clean combustion (Lee et al., 2020). The use of low amounts of NG in diesel engines can be the best solution (You et al., 2020b). In the research of Akbarian and Najafi (2019), the low amounts of NG in diesel engines were investigated; according to their results, using the NG in diesel engine improved performance and emission. Therefore, the possibility of using high amounts of NG in diesel engines should be investigated to determine their impact on engine performance and emissions.

On the other hand, predicates show the inability to supply diesel fuel from 2015 to 2040. According to the International Energy Agency (IEA), Asian countries will see demand growth of 15 million barrels per day by 2040. This indicates that it will be difficult to supply fossil fuels due to increasing demand. On the other hand, to deal with environmental pollution and reduce global warming, countries are obliged to reduce fossil fuels' consumption. Therefore, these factors are among the main reasons that increase the need to find alternative fuels. As a starting point, this assessment makes it more possible to move towards the use of renewable energy (Solé et al., 2018). Also, generated electricity from diesel engines by 2025 will not provide the required energy, but by expanding renewable energy sources such as biofuels and biomass energy, the energy supply will be possible by 2040 (Capellán-Pérez et al., 2014). Sustainable technologies for the production of alternative energy sources in the form of biofuels and biomass by focusing on the use of renewable sources are gradually expanding. Biodiesel is one of the most attractive biofuels. If biodiesel is produced from waste oils, it can compete with conventional fuels (Najafi et al., 2019; Khalife et al., 2017; Najafi et al., 2018b,a). Biodiesel is a renewable fuel to supply energy demand and reduce greenhouse gas emissions (GHG), rapidly increasing (Khan et al., 2019; Hajlari et al., 2019; Karimi et al., 2020; Ghazanfari et al., 2017; Jannatkhah et al., 2020). Biodiesel contains 10 to 12% oxygen in its chemical structure, which reduces exhaust gas emissions (Akbarian and Najafi, 2019; Noor et al., 2018). Research shows that using biodiesel can significantly reduce CO emissions, the attendance of low carbon in biodiesel's chemical structure, and consequences in clean combustion than diesel fuel (Najafi and Khani, 2011; Noor et al., 2018). The Trans-esterification method is usual in the biodiesel production process. Biodiesel can be mixed with diesel fuel in any proportion. Currently, the use of 5% biodiesel and diesel fuel blends (B5) is usual, and most countries have planned to use B20 fuel (Lewis et al., 2009). A combination of Biodiesel with diesel has a direct effect on the physical properties of the fuel. Physical properties of the fuel influenced the fuel atomization, so the process changing the fuel consumption, energy release, and performance of the diesel engine during the combustion phase compared to diesel. Therefore, high increasing the biodiesel in the fuel blend, needed more reformation at the engine structures. Therefore, adding biodiesel to diesel fuel was occurred at the suitable amount. Researches show that biodiesel can be the ability to used up to 20% in the diesel engine, and by this amount not needed to changing the engine structure for example fuel injector, piston form, and other parameters of the engine (Attia et al., 2018).

In the process of biodiesel production by trans-esterification, one of the products of biodiesel production is glycerol, which accounts for at least 10 vol% of the resulting mixture. Glycerol is a by-product of this process; various options have been identified for its utilization (Pitt et al., 2019). Increased biodiesel production leads to additional raw glycerol, representing a big problem in the biodiesel production process. It has created new challenges for sustainable use. Although a few ranges of applications have for the utilization of raw glycerol Monteiro et al. (2018); but, glycerol recycling into more valuable materials can be a better solution. So, the biological synthesis of additives from glycerol, such as acetyl glycerides, is an economical and alternative method. Recycling ways to produce valuable materials from glycerol have been proposed to improve the biodiesel production industries. The etherification method may be a suitable method for converting glycerol to a fuel additive compared to other methods (Marinho et al., 2020); because ether compounds improve some physical properties of the diesel fuel (Natsir and Shimazu, 2020). These additives have the ability to utilization in petroleum fuel blends (Liu et al., 2019). Products of the glycerol etherification process with isobutene include glycerol ethers are more suitable for use to fuel mixtures, it is due to their better mixing properties (Bozkurt et al., 2015). So, finding a suitable combination of raw glycerol and utilization as a fuel additive, not only reduce its negative impact on the environment but also, it is more substantial to increase the economic benefits of biodiesel production.Table 1, shows the effect of adding these materials on the engine performance and emission, at the diesel engine:

According to the researches of Table 1, the effect of the Triethylene glycol mono methyl ether (TGME) additive was not investigated on the performance and emissions of SFM and DFM engines. Therefore, due to the mentioned advantages of the etherification method, glycerol was converted to fuel additive by this method. In summary, the objective and scope of this study are to examine the following:

Table 1
Effects of glycerol additives on engine performance and emissions.

Row	Research	Glycerol additives	Engine performance	Engine emission	Ref.
1	Beatrice et al. (2014)	Glycerol ethers (GEM)	Diesel and GEM mixtures have not shown a significant effect on engine performance and efficiency.	Exhaust emissions at the average load conditions have a 70% reduction in CO emissions, while there is a slight increase in NOx emissions.	Beatrice et al. (2014)
2	Yesilyurt and Aydin (2020)	Diethyl ether (DEE)	Experimental results showed that when 10% of diethyl ether was added to the fuel mixture, the brake power was decreased by 17.17% compared to pure diesel, while the specific fuel consumption increased by 29.15%.	Adding this additive on average reduces the number of greenhouse gases and NOx compared to diesel engines by 12.89 and 8.84%. However, with a further increase in this additive, CO emission showed an increasing trend compared to diesel fuel.	Yesilyurt and Aydin (2020)
3	Dinesha et al. (2019)	Diethyl ether	Diethyl ether is used to improve combustion efficiency in emulsified mixtures. Compared to biodiesel performance, the brake thermal efficiency of emulsified fuel slightly increases with the diethyl ether, and also the maximum brake thermal efficiency was obtained with 2% of diethyl ether blend.	The carbon monoxide emissions were low for emulsified mixtures.	Dinesha et al. (2019)
4	Jeevanantham et al. (2019)	Diethyl ether (DEE) and methyl tri-butyl ether (MTBE)	Experimental results showed that the triple mixture D50-B45-DEE5 reduced the thermal efficiency by 3.5% compared to other triple mixtures.	The triple mixtures of D50-B45-MTBE5 and D50-B45-DEE reduced the CO emissions by 8.1 and 14.8%, respectively, compared to diesel fuel. Also, D50-B40-DEE10 and D50-B40-MTBE10 mixtures reduced NOx emissions by 32% and 8.8%, respectively.	Jeevanantham et al. (2019)
5	Wu et al. (2017)	Ethylene glycol	The engine performance of Ethylene glycol is comparable to ethanol and ethyl acetate. There is no significant difference in the brake specific fuel consumption and the exhaust gas temperature amounts for the 10%Vol of Ethylene glycol and diesel mixtures.	At the 10%Vol Ethylene glycol in the diesel fuel blend reduced NOx emissions, but other emission parameters not changed.	Wu et al. (2017)
6	Sezer (2011)	Dimethyl ether and diethyl ether	For dimethyl ether and diethyl ether at a similar condition and constant amounts of 3%Vol, the brake power is reduced by about 32.1% and 19.4% at 4200 rpm, while the brake specific fuel consumption was increased by about 47.1 and 24.7% at 2200 rpm, respectively.	Low carbon dioxide is obtained in any conditions by 3%Vol of Dimethyl ether and dimethyl ether, while under the same conditions, carbon monoxide and nitrogen oxide are slightly higher for dimethyl and diethyl fuel blends.	Sezer (2011)

Table 2
The specifications of the produced biodiesel based on the GC-Mass results.

Ester type	Formula	wt.%	Ester type	Formula	wt.%
Octanoic acid	$C_8H_{16}O_2$	0.74	Oleic acid	$C_{18}H_{34}O_2$	42.28
Lauric acid	$C_{12}H_{24}O_2$	3.49	Linoleic acid	$C_{18}H_{32}O_2$	1.22
Myristic acid	$C_{14}H_{28}O_2$	11.59	Nonadecanoic acid	$C_{19}H_{38}O_2$	0.14
Pentadecanoic acid	$C_{15}H_{30}O_2$	7.17	Eicosatrienoic acid	$C_{20}H_{34}O_2$	9.29
Linoleic acid	$C_{16}H_{28}O_2$	20.25	Heneicosylic acid	$C_{21}H_{42}O_2$	0.18

- Converted the glycerol to fuel additive by etherification method. Glycerol returning to the fuel cycle is a novel and very viable solution. Triethylene glycol mono-methyl-ether (TGME) is obtained from glycerol recycling by the etherification method.
- Investigation of the effect of the TGME additive on performance and emissions of SFM and DFM engines. It is necessary to evaluate the engine performance and emissions of this novel glycerol additive to determine the best conditions for using this compound.
- Investigated the effect of the TGME additive on the DFM engine by using high amounts of NG in diesel engines to determine their impact on engine performance and emissions. Wang et al. (2019), used natural gas in the diesel engine at the amounts of 20, 30, 40, and 50%, but were not investigated the effect of using high amounts of natural-gas on the engine performance and emissions. So, in this study, natural-gas was used at 60, 70, and 80% amounts.
- Investigated the effect of the TGME additive on the brake thermal efficiency and generated power cost parameters of the diesel engine.

Therefore, for the first time, the TGME additive was investigated under different percentages with biodiesel fuel (B5 and B20) at the SFM and DFM engines in various amounts of NG to find suitable conditions for improving engine performance and emissions. Dual-fuel combustion has been performed through the use of natural-gas as the main fuel and diesel/biodiesel blend. Also, suitable generated power cost conditions for the use of this additive was evaluated.

2. Material and method

2.1. Process of biodiesel and glycerol additive production

In this research, biodiesel was produced from waste cooking oil (WCO) by using the process of trans-esterification (Fig. 1). 800

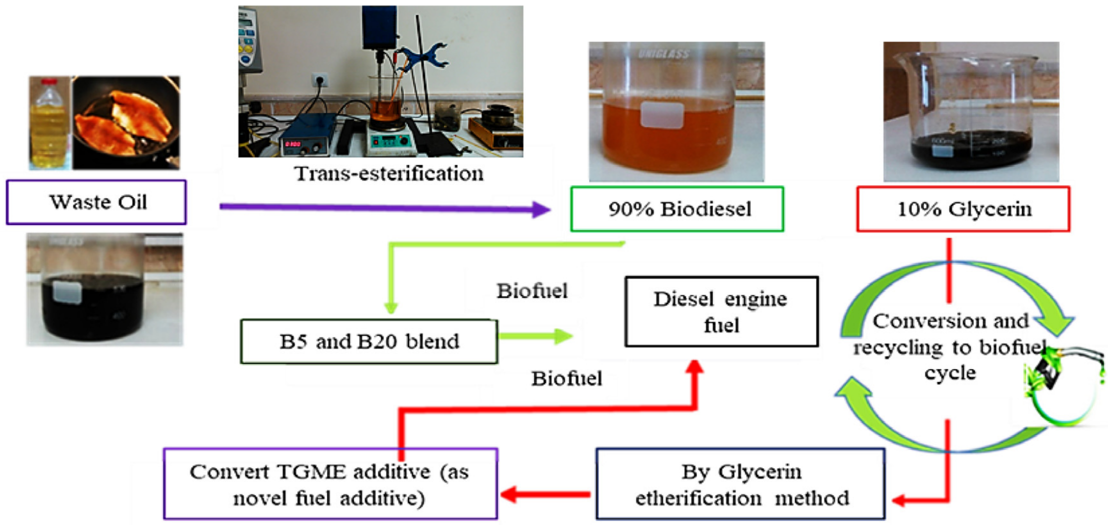

Fig. 1. Glycerol conversion and recycling into the fuel cycle as a fuel additive.

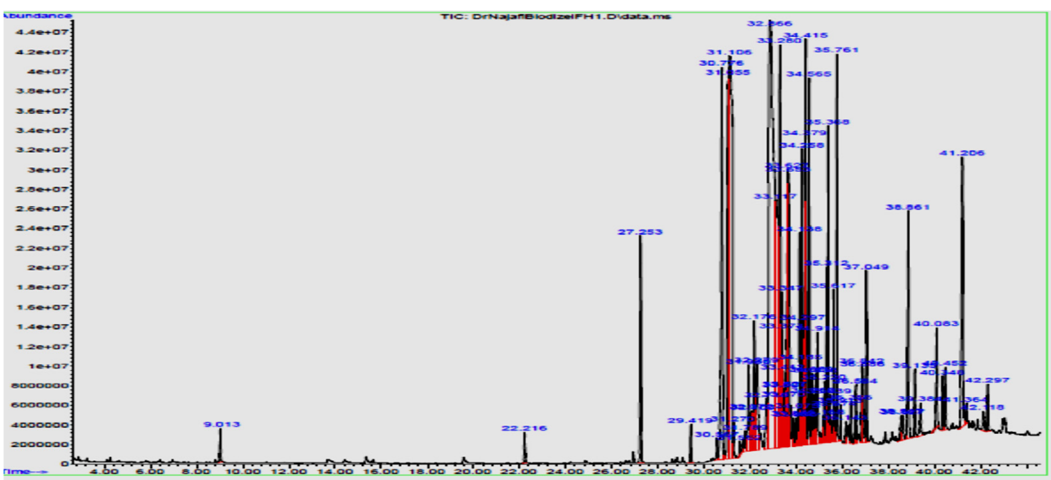

Fig. 2. GC-Mass result for WCO biodiesel.

g of WCO heated to 70 °C; then methanol with a molar ratio of 6:1 was added to the WCO; sodium hydroxide 1% (based on weight) heated with methanol to 70°C. Then, the contents of these two containers were added together at the same temperature of 70°C. It is mixed with 600 rpm for 30 min. After separating the biodiesel from the glycerol material, the biodiesel was washed to remove excess material (Ghazanfari et al., 2017). The amount of glycerol material compared to biodiesel was about 1 to 10. For achieving high percent biodiesel, this emulsion was washed three times with distilled water, the distilled water washing method was performed at 50°C (Ghazanfari et al., 2017). Gas chromatography (GC-Mass) test was performed to identify biodiesel chemical compounds. The tested gas chromatography device consisted of mass spectrometry GC: 7890A, MS: 5975C together a tube with an inner diameter of 0.25 mm and a length of 30 m. The test was performed according to ASTM D6584 standard. The result of the GC-Mass test was demonstrated in Fig. 2; The percentage of different esters in the composition was extracted from Fig. 2 and listed in Table 2. According to Table 2, in the produced biodiesel from waste oil, the percentage of octadecanoic acid, hexadecanoic acid, and tetradecanoic fatty acid esters were higher. Table 2 and Fig. 2 show the specifications of the produced biodiesel based on the GC-Mass results.

Glycerol is a chemical product that colorless, odorless, and viscous at 25°C; its commercial name is glycerol (Christoph et al., 2000). Glycerol ethers are produced by the glycerol etherification method, by using the iso-butene in the presence of homogeneous acid catalysts (Vlad et al., 2011). Ethylene glycol is a chemical compound. Ethylene glycol can be dissolved in any proportion with water. Mono-ethylene glycol is obtained from ethylene oxide; in this reaction, ethylene oxide reacts with water to form mono-ethylene glycol. Tri-ethylene glycol is an odorless, colorless, and viscous liquid compound. Glycerol conversion and recycling into valuable fuel additive substances are important. The process of TGME production was demonstrated in Fig. 3. To produce TGME from glycerol, firstly, glycerol material was hydrogenated during the glycerol reduction process (GRP) in the presence of Ni metal catalyst (according to Dasari et al., 2005); During this process, ethylene glycol produced along with the CH_3OH. In the next step, the TGME additive is produced using the Glycerol Etherification Process (GEP); this reaction performed at a temperature of 100–150 °C using isobutene.

To mono-ether production, glycerol is reacting with one mole of isobutene at these temperatures. Therefore, isobutene with a molar ratio of 1:1 used to produce the TGME additive; also, acid catalysts were used in the GEP to increase glycerol conversion and selectivity rate (according to Behr and Obendorf research Behr

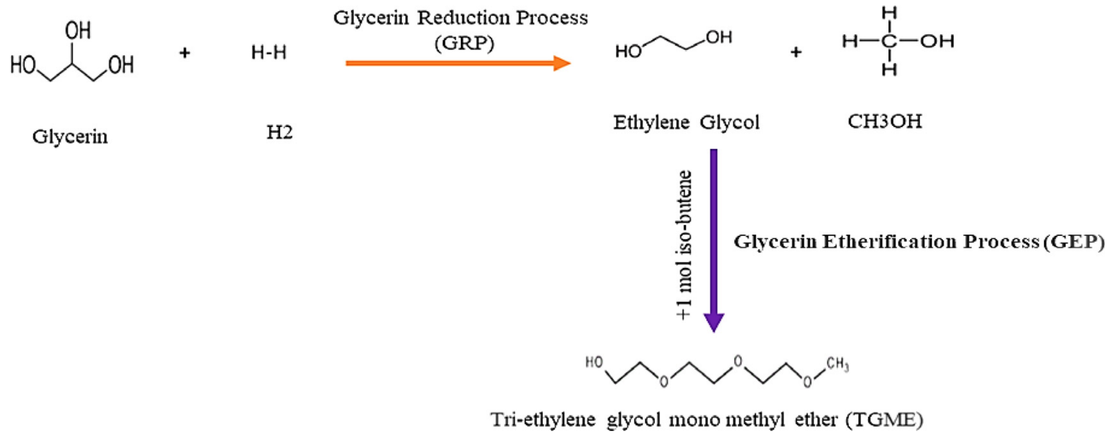

Fig. 3. The process of converting glycerol to TGME additive.

Table 3
Physical properties of TGME additive and its comparison with other fuels.

Type	ASTM standard	Diesel	Natural gas	Biodiesel	Glycerol	TGME additive
Density 15 °C (g/cm^3)	D4052	0.841	0.55	0.892	1.261	0.996
Flash point (°C)	D93	74	–	139	160	110
Viscosity 40 °C (mm^2/s)	D445	4.2	–	5.04	7.15	4.19
Cloud Point (°C)	D5773	−6	–	8	15	−68
Low Heat Value (MJ/kg)	D240	44.58	49.1	38.79	4.32	24.29
Molecular Formula	–	$C_{14}H_{24}$	CH_4	$C_{17}H_{34}O_2$	–	$C_7H_{16}O_4$
Molecular mass (g/mol)	–	192	16.04	270	–	164.20
Cetane number	D613	55	–	50	–	–
C (%)	–	87.5	74.8	75.5	–	51.15
H (%)	–	12.5	24.9	12.6	–	9.74
O (%)	–	–	–	11.9	–	38.97

and Obendorf, 2002). A high conversion rate was achieved by this method. The physical properties of the TGME additive were obtained according to the ASTM D6751a standard (Table 3). Fuel properties were measured based on the ASTM standard. The density of fuel samples was measured by ASTM D4052, using the DA-130N Digital Densitometer. The measurement accuracy of the device is equal to +0.001 g/cm^3. The heat value of the samples was measured using a Parr calorimeter bomb device by ASTM D240. The cloud point of the samples was determined according to ASTM D5773. The viscosity of fuel samples was measured using Brookfield DV-II Prime viscometer, equipped with a UAL adapter, by ASTM D445 standard at 40°C. The flashpoint temperature was measured by ASTM D93.

Therefore, this Table demonstrated that TGME has some features that can make it a suitable additive for use in diesel engines. For example, a low cloud point of the fuel can be an advantage. Also, the presence of more oxygen in its structure can be the main reason for choosing this additive for use in diesel fuel blends.

2.2. Fuel blends

In this study, the TGME additive was added to the mixture of biodiesel (B5, B20) and diesel at different percentages (0.1, 0.2, 0.3, and 0.4 vol%) and investigated in two modes: SFM and DFM engines. In the DFM engine, the different NG conditions were investigated. The qualification of high NG utilization has not been studied at the diesel engine (according to the introduction section). So, this present study investigated these values at 60, 70, and 80% of natural gas; Eq. (1) was used to adjust the amount of the desired NG. In the DFM engine by replacing part of diesel fuel with NG fuel, the combustion occurred; the NG was mixed with air by mixer setup (Fig. 4). In the DFM engine, the NG rates were regulated according to Eq. (1); in this equation, the rate of the natural gas amount to Total fuel was demonstrated (NG%). The NG mass flow (cc/s) and diesel fuel mass flow (cc/s) were demonstrated by $\dot{m}_{NG}$ and $\dot{m}_{D}$, respectively.

$$NG\% = 100 \times \frac{\dot{m}_G}{\dot{m}_{NG} + \dot{m}_D} \tag{1}$$

After these steps, the fuel samples were arranged according to the Table 4. Each of the fuel samples was investigated in different states of NG (60, 70, and 80%) under DFM engine conditions.

In this study, engine tests were carried out to select suitable fuel samples with appropriate engine performance and emissions. To accurately investigate the effect of different amounts of additive, the variable parameters included only fuel compounds; and other performance parameters such as fuel injection angle, engine speed, and engine load were constant for all conditions. The physical properties of the produced fuels were tested by the biodiesel standard (Table 5).

Also, for TGME-Biodiesel/Diesel fuel blends were investigated the miscibility and oxidation stability. The stability of fuel blends was proven after 30 days. It was observed that adding 0.1, 0.2, 0.3, and 0.4 vol.% of TGME to Diesel, B5, and B20 compounds retain a suitable homogeneous mixture over one month.

2.3. Engine performance analysis

In this study, a single-cylinder diesel engine was used for testing (Kirloskar DA10, India). The engine tests were carried out at full-load and 1500 rpm. In all tests, the engine was firstly powered by diesel fuel and under idle conditions. After 15 min, the generated electricity was transferred to the electric consumer (heater) by changing the variable electrical resistance status. The electricity was generated by the generator. The generated electricity was transferred to the heater with the voltage regulator set-up and consumed. The engine was regulated at the full-load. Input air temperature and exhaust gases were measured using

Table 4
The fuel samples.

Row	Samples name		Amounts (%Vol.)			
	Diesel fuel blends	NG	Diesel	Biodiesel	TGME	NG%
1	M0	NG 60-70-80	100	0	0	60-70-80
2	M 0.1	NG 60-70-80	99.9	0	0.1	60-70-80
3	M 0.2	NG 60-70-80	99.8	0	0.2	60-70-80
4	M 0.3	NG 60-70-80	99.7	0	0.3	60-70-80
5	M 0.4	NG 60-70-80	99.6	0	0.4	60-70-80
6	B5	NG 60-70-80	95	5	0	60-70-80
7	B5M 0.1	NG 60-70-80	94.9	5	0.1	60-70-80
8	B5M 0.2	NG 60-70-80	94.8	5	0.2	60-70-80
9	B5M 0.3	NG 60-70-80	94.7	5	0.3	60-70-80
10	B5M 0.4	NG 60-70-80	94.6	5	0.4	60-70-80
11	B20	NG 60-70-80	80	20	0	60-70-80
12	B20M 0.1	NG 60-70-80	79.9	20	0.1	60-70-80
13	B20M 0.2	NG 60-70-80	79.8	20	0.2	60-70-80
14	B20M 0.3	NG 60-70-80	79.7	20	0.3	60-70-80
15	B20M 0.4	NG 60-70-80	79.6	20	0.4	60-70-80

Table 5
Physical properties of fuels.

Row	Sample		Flash point (°C)	LHV (MJ/kg)	Density (g/cm^3)	Viscosity (mm^2/s)	Cloud point (°C)
	Diesel fuel blends	NG	ASTM D93	ASTM D240	ASTM D4052	ASTM D445	ASTM D5773
1	M0	NG0	74	44.58	0.841	4.2	−6
2	M 0.1	NG0	82.3	43.92	0.849	4.2	−5.6
3	M 0.2	NG0	82.8	43.84	0.851	4.18	−5.1
4	M 0.3	NG0	83.2	43.61	0.852	4.17	−5.9
5	M 0.4	NG0	84.6	43.47	0.855	4.15	−5.4
6	B5	NG0	86	42.56	0.862	4.62	−4.7
7	B5M 0.1	NG0	86.8	42.35	0.870	4.59	−4.3
8	B5M 0.2	NG0	87.4	42.28	0.873	4.54	−4.1
9	B5M 0.3	NG0	87.9	42.14	0.875	4.5	−4.7
10	B5M 0.4	NG0	88.1	42.01	0.878	4.45	−4.4
11	B20	NG0	88	41.64	0.884	4.92	−3.9
12	B20M 0.1	NG0	88.2	41.48	0.889	4.86	−4
13	B20M 0.2	NG0	88.6	41.31	0.893	4.84	−3.4
14	B20M 0.3	NG0	88.9	41.2	0.897	4.78	−3.6
15	B20M 0.4	NG0	89.5	41.12	0.898	4.74	−3.2

Table 6
The specifications of the used single cylinder DI diesel engine.

Engine type	Vertical, Four-stroke
Bore and Stroke	102 × 116 mm
Displacement volume	0.9481 L
Max. Brake Power	7.4 kW @ 1500 rpm
Fuel injection timing	26° CA BTDC
Compression ratio	17.5:1
Type of Cooling	Water
Injection pressure	200 Bar
BMEP 1500 rpm	6.21 Bar

a K-type thermocouple. A 12 cc pipette was utilized for measuring fuel consumption, employing two inlet and outlet valves at the top and bottom. In this research, the fuel injection was performed at the 26°CA-BTDC and 200 bar. The laboratory set-up with equipment was demonstrated in Fig. 4. Also, the tested engine specifications in this study listed in Table 6. Also, the brake force was measured by the load cell. These engine tests were performed in the laboratory room with pressure and temperature of 102.4 ± 0.2 kPa and 25 ± 1°C.

A combustion gas Analyzer-KIGAZ 210 was used to measure engine emissions parameters. The complete combustion reaction for this fuel compound is as follows (Eq. (2)). Also, the other substantial parameters of the engine such as brake power (BP), Brake specific fuel consumption (BSFC), and equivalence coefficient (φ) equations, were calculated.

$$\begin{aligned} & n_1C_{14}H_{24} + n_2C_{17}H_{34}O_2 + n_3CH_4 + n_4C_7H_{16}O_4 \\ & \quad + a_s\,(0.21O_2 + 0.79N_2) \rightarrow n_7CO_2 + n_8H_2O + n_9N_2 \end{aligned} \tag{2}$$

The BP was calculated; in this equation, the amount of Torque (N.m), and engine speed (rpm) were demonstrated by T, and N parameters, respectively. Also, the BSFC was calculated by Eq. (3); in this equation, the amount of fuel mass flow (cc/s) was demonstrated by $\dot{m}_S$ parameter.

$$\mathrm{BSFC} = \frac{3600 \times 1000 \times \dot{m}_s}{\mathrm{Bp}} = (3600 \times 1000 \times \dot{m}_s)/\left(\frac{2\pi nT}{60}\right) \tag{3}$$

The Equivalence Coefficient (φ) was calculated by Eq. (4); in this equation, the amount of Air mass flow (cc/s), Fuel mass flow (cc/s), air to fuel ratio in standard conditions, and air to fuel ratio in actually condition were demonstrated by $\dot{m}_{air}$, $\dot{m}_s$, A/F_s, and A/F_a parameters, respectively.

$$\varphi = \frac{A/F_s}{A/F_a} = \left(\frac{a_s(0.21 \times 2 \times 16 + 0.79 \times 2 \times 14)}{n_1(192) + n_2(270) + n_3(16.04) + n_4(164.2)}\right)/\left(\frac{\dot{m}_{air}}{\dot{m}_s}\right) \tag{4}$$

The fuel power (P_{fuel}) was calculated; in this equation, the amount of Low Heat Value (MJ/kg), and fuel mass flow (cc/s) were demonstrated by LHV, and $\dot{m}_S$, parameters. The engine was desired as a thermodynamical system (Fig. 5), and the brake thermal efficiency (BTE) was calculated by Eq. (5).

$$\mathrm{BTE} = \frac{\mathrm{Bp}}{P_{fuel}} \times 100 = \frac{\mathrm{Bp}}{\dot{m}_s \times \mathrm{LHV} \times 1000} \times 100 \tag{5}$$

Due to device measurement error, data uncertainty was calculated according to Eq. (6) (You et al., 2020b; Jannatkhah et al.,

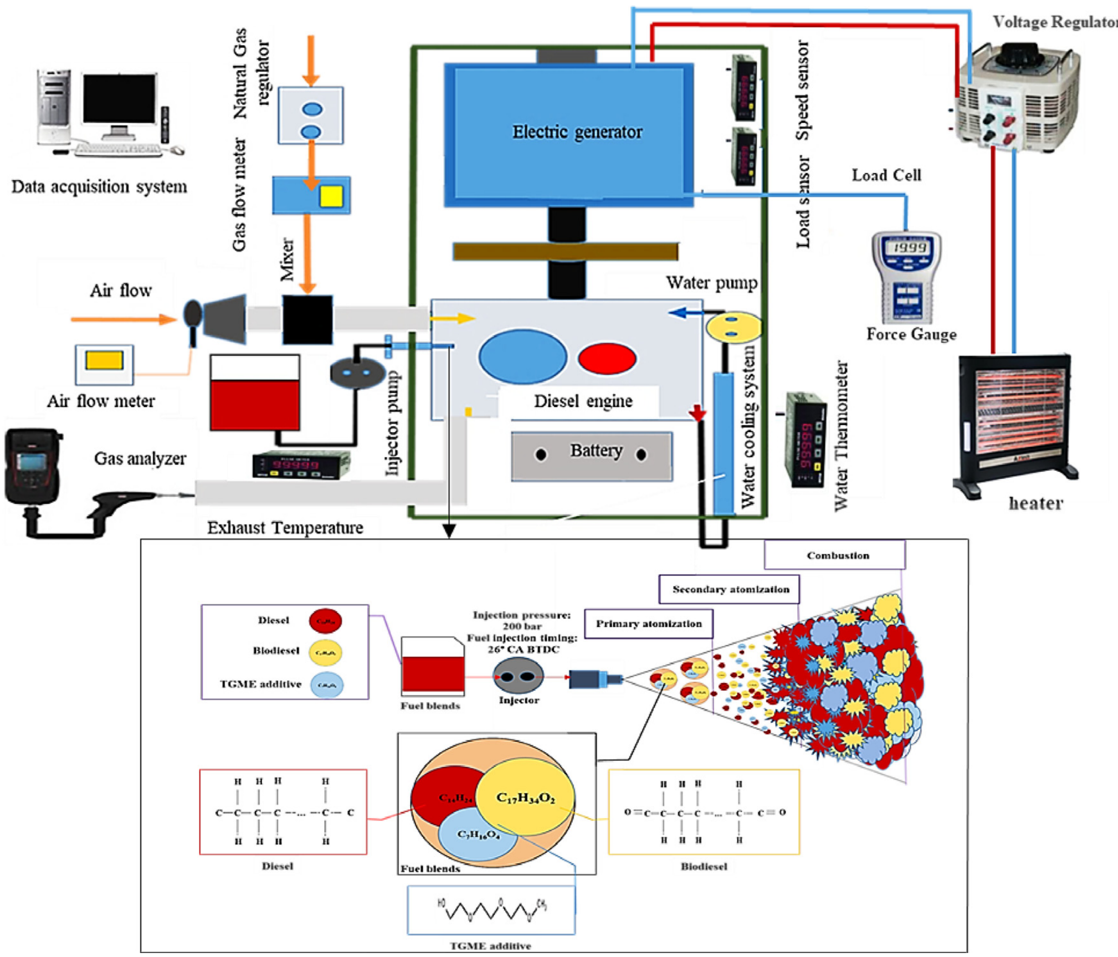

Fig. 4. The laboratory set-up.

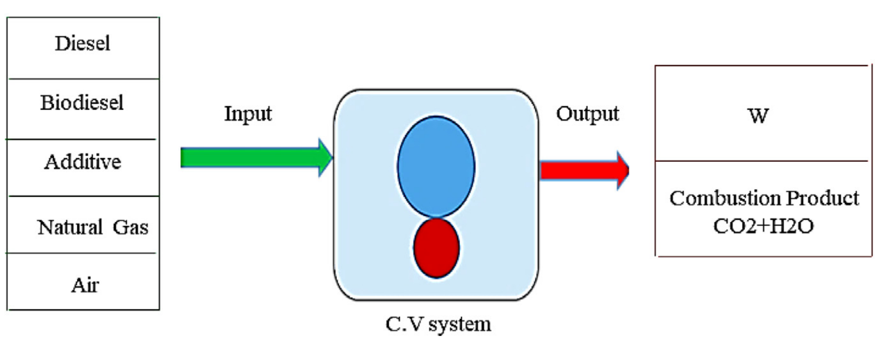

Fig. 5. Thermodynamical system (C.V).

2020). Where δ_R is the amount of uncertainty, R is the response function, X_1, X_2, X_3, …, and X_n are independent variables, δ_1, δ_2, δ_3, …, and δ_n are symbols of the uncertainty of each independent variable.

$$\delta_R = \left[\left(\frac{\partial R}{\partial X_1}\delta_1\right)^2 + \left(\frac{\partial R}{\partial X_2}\delta_2\right)^2 + \left(\frac{\partial R}{\partial X_3}\delta_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n}\delta_n\right)^2\right]^{\frac{1}{2}} \tag{6}$$

In all experimental tests, the accuracy of the measured data was validated. The error and range for the output numbers of the test results are as follows (Table 7).

3. Results

This section presents the results of engine tests in the SFM and DFM engine. The effect of the TGME additive on fuel combustion is discussed in this section. Also, it is reflected in the analysis of BSFC, φ, EGT, BTE, and exhaust emissions, such as NOx and CO_2. At the DFM engine, different NG conditions (NG60, NG70, and NG80) was demonstrated. Each Figure itself contains various combinations (60 fuel samples) of pure diesel fuel, TGME additive (M0.1, M0.2, M0.3, and M0.4), and biodiesel (B5 and B20). The baseline for all performance and emission parameters comparison was conventional diesel combustion. In all figures, the comparison of engine results was performed between different fuel blends and pure diesel fuel. In all Figures, the M0 symbol demonstrated the

Table 7
Specifications and accuracies of measuring instruments.

Parameter	Unit	Range	Resolution	Accuracy	Uncertainty (%)
Engine speed	rpm	1 to 9999	1 rpm	±1%	1.12
Air flow	m/s	0–10	±1	0.01 m/s	3.92
Load	N	0–100	±1	0.1 N	1.021
NG flow meter	CC	0–10 000	±1	0.1 CC	1.794
CO	ppm	0–8000	1 ppm	±1	–
CO_2	% Vol	0–99	0.1%	±1	–
NOx	ppm	0–5155	1 ppm	±1	–
Exhaust temperature	°C	0–850	± 0.35	1 °C	–

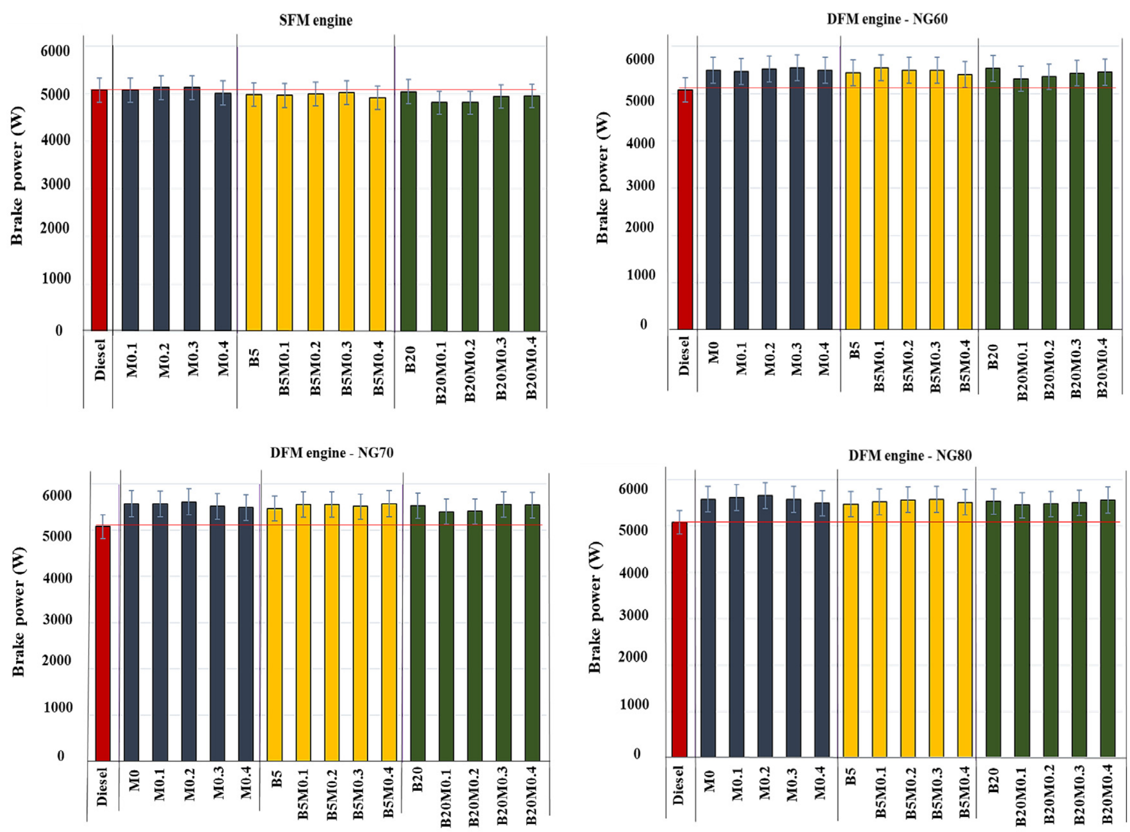

Fig. 6. Effects of TGME additive, NG, B5, and B20 fuel blends on the BP.

condition that used pure diesel with together NG fuels in the engine (without biodiesel and TGME additive).

3.1. Effect of TGME additive, NG, B5, and B20 fuel blends on the BP

BP is one of the most important performance parameters of the engine. According to Fig. 6 results, adding the TGME additives into diesel blend slightly increased the BP; this condition was also slightly higher at 0.2 and 0.3 vol% TGME additives; the reason for this BP increase related to the improvement of fuel combustion properties (Natsir and Shimazu, 2020), and presence of oxygen in the fuel structures (Table 3). Every fuel element needs to react with oxygen for complete combustion, so it is very substantial to provide enough oxygen to achieve a proper combustion process. By 0.2 vol.% TGME additive, the BP amount was increased by 1.07% compared to pure diesel fuel. The presence of oxygen in the chemical structure of the TGME additive can make it a suitable oxygenated additive. The presence of oxygen in the fuel's chemical structure increases respiratory efficiency and makes it possible to increase the engine's brake thermal efficiency. Also, it can be concluded that with better combustion due to the presence of sufficient oxygen, it converts more of the chemical energy of the fuel into thermal energy. Also, the studies by Han et al. (2020), and Nabi et al. (2020), reported that oxygenated fuels contribute to the ignition process and improved combustion. But due to the low LHV and high flash point of TGME additive (in comparison to diesel), by adding this substance at 0.4 vol% TGME into diesel fuel blends, the combustion process was changed. Therefore, providing the required amount of oxygen improves the combustion process. However, the presence of more oxygen than required in the fuel composition reduces the LHV and lead to changes in the combustion process. Therefore, by using the 0.4 vol% TGME in the diesel fuel blend, the BP was slightly decreased compared to pure diesel. After the fuel injection, the third process occurred: primary atomization, secondary atomization, and combustion (Zhang et al., 2020). The physical parameters of fuel can change this atomization process and combustion. In this research, the fuel injection was performed at the 26°CA BTDC and 200 bar. According to the Table 3, the fuel's physical parameters can understand that the TGME additive compared to biodiesel blends, was faster, flammable, and ignited earlier. Therefore, these conditions affected the combustion process and changed this process.

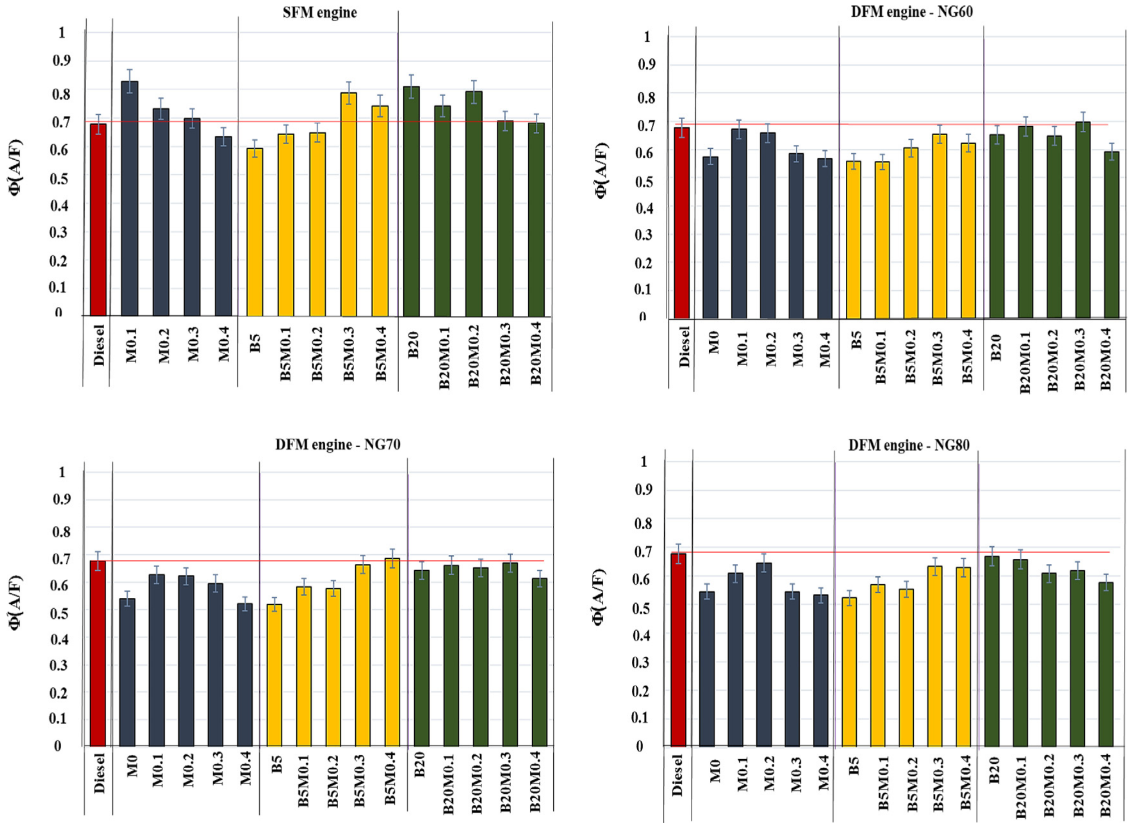

Fig. 7. Effects of TGME additive, NG, B5, and B20 fuel blends on the equivalence coefficient (φ).

Adding biodiesel to this fuel blend reduces the amount of BP compared to pure diesel fuel, also these values more decrease for B20. By 0.3 vol% TGME additive in B5 fuel blend, the BP amount was reduced by 1.04% compared to pure diesel fuel. The reason for this BP decrease can be related to the increase in fuel density (Table 5). The fuel density and viscosity increased by biodiesel (Das et al., 2018), and the most physical parameters of fuel changed (Hwang et al., 2016). Thus, this parameter affected engine performance. Also, due to the high flash point of biodiesel (according to Table 3), by adding this substance the combustion process was more changed. According to the fuel's physical parameters (high flash point), the biodiesel ignited later than diesel and TGME blends (Table 3). This parameter can also lead to incomplete fuel combustion at the desired time (Zhang et al., 2020; Kalsi, 2017). Also, part of the fuel energy is lost. So, this condition reduced BP. This parameter can also affect engine emissions. For the DFM engine condition, the BP was higher than the SFM engine in all moods. Due to the low-density value of the NG in the combustion chamber (Table 3); because the low-density cause to complete the combustion of the fuel and thus increases the BP. Furthermore, increasing the NG amount could lead to an improvement in the combustion, an enhance in the degree of constant volume combustion, and an increment in the Heat Release Rate (HRR) during the premixed combustion phase (Kalsi, 2017). Also, according to the studies by Akbarian and Najafi (2019), and Sharma and Kaushal (2020), the engine's performance was more improved in DFM engine conditions. The addition of TGME additive in different amounts at the SFM and various modes of DFM engine altered BP, but the highest value was obtained in the case of NG80 and 0.2 vol.% TGME additive. In these conditions, the BP was 11.3% higher than diesel engines.

3.2. *Effect of TGME additive, B5, and B20 fuel blends on the equivalence coefficient (φ)*

The equivalence coefficient is one of the engine performance parameters. During this ratio, the amount of Air to Fuel (A/F) is measured (Eq. (4)). Fig. 7 shows the conditions for the use of different amounts of TGME additive and biodiesel in SFM and DFM engines.

In the SFM engine, adding the TGME additive (at the 0.4 vol%) to diesel fuel increases the fuel density (Table 5) and thus increases the A/F_a amount. This reduces the fuel equivalence coefficient (Eq. (4)). The changes in the diesel fuel's physical parameters can affect engine performance (Elkelawy et al., 2019); adding biodiesel (B5) to diesel fuel increases the fuel density and changes the physical parameters of the fuel. Also, in the DFM engine condition, the addition of biodiesel to diesel fuel has a more impact on engine performance and reduces the equivalence coefficient. At the DFM engine conditions, the engine performance was further modified (Kan et al., 2020). Therefore, under DFM engine condition, B5 and B20 in the diesel fuel blends resulted in more efficient modes; When biodiesel and TGME additive were added to pure diesel fuel, the fuel density is more increased (Table 5). And this had led to an increase in A/F_a amount and a decrease in the equivalence coefficient.

3.3. *Effect of TGME additive, NG, B5, and B20 fuel blends on the BSFC*

BSFC is one of the most important engine performance parameters. Researchers are searching to reduce the BSFC parameter because it reduces the cost and amount of consumed fuel. By 0.2 vol.% TGME additive, the BSFC amount was reduced by 16.92% compared to pure diesel fuel. Additional TGME additive in the SFM engine has reduced the BSFC; this is due to high BP. Of

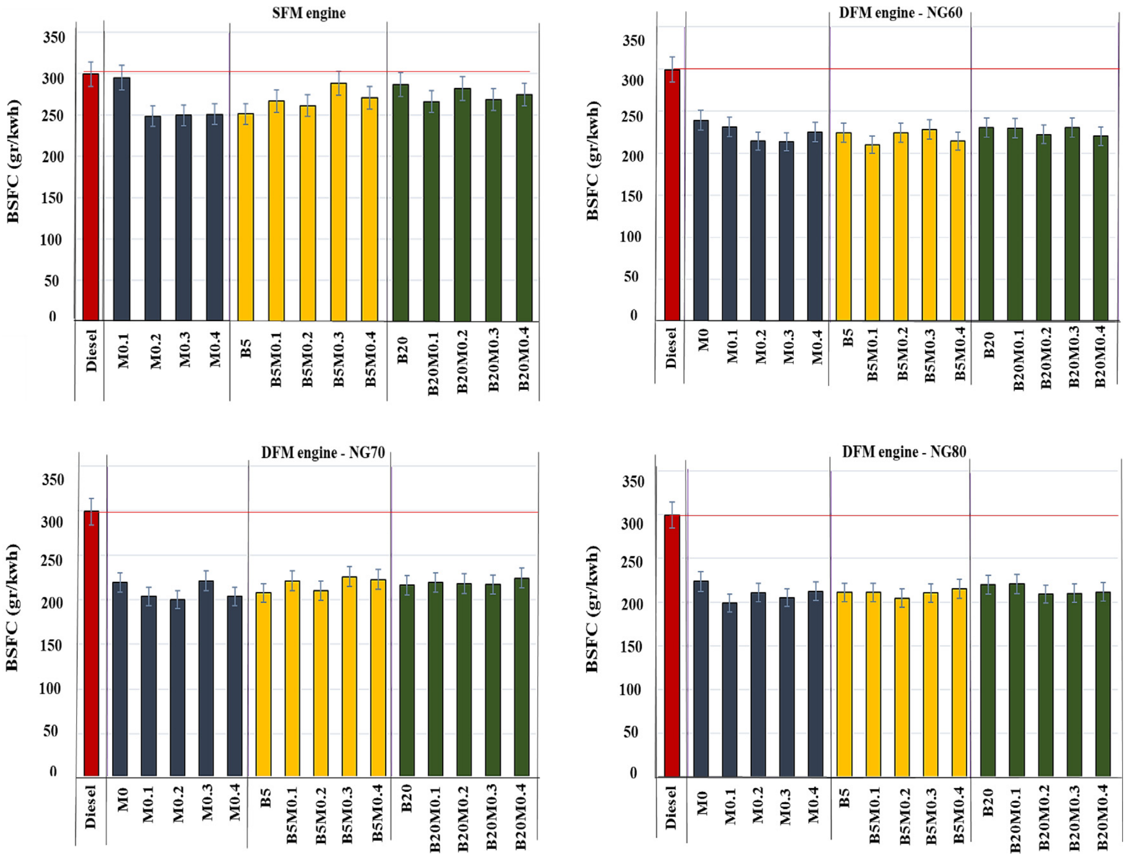

Fig. 8. Effects of TGME additive, NG, B5, and B20 fuel blends on the BSFC.

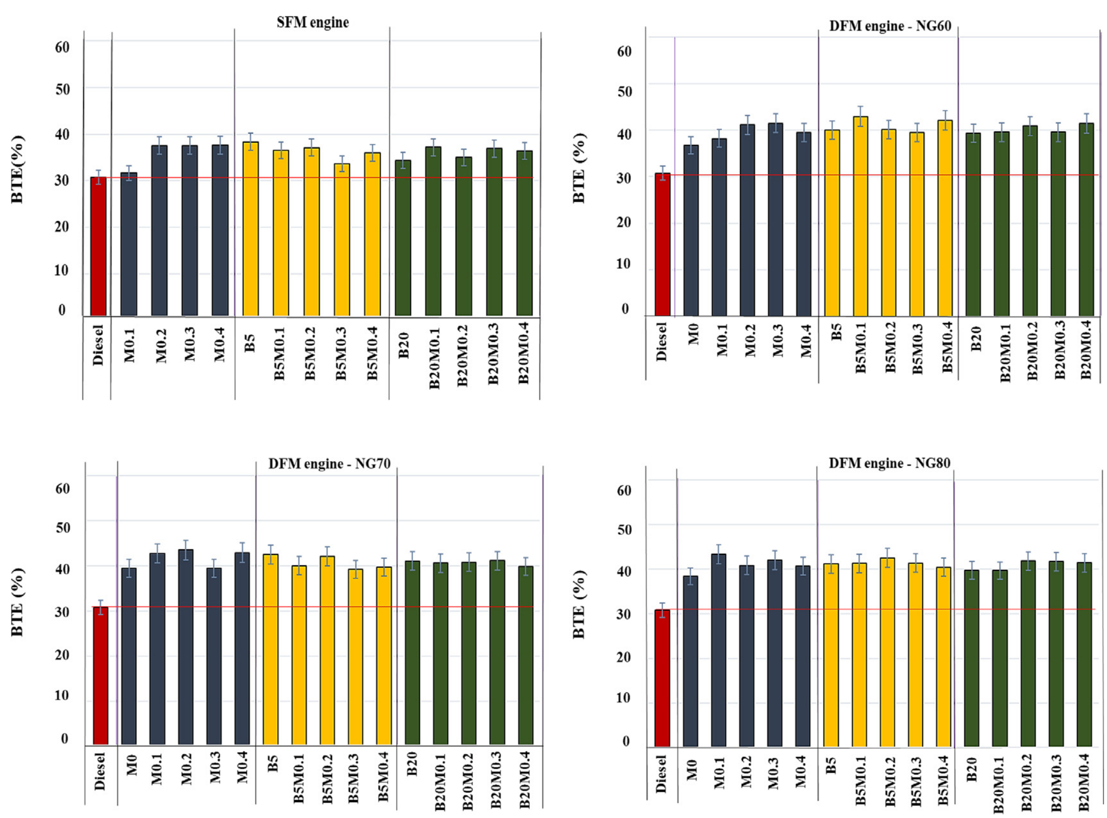

Fig. 9. Effect of TGME additive, NG, B5, and B20 fuel blends on the BTE.

course, the presence of oxygen in the fuel blend also affected the combustion process (Section 3.1). Because oxygenated compounds can improve fuel quality (Zhang et al., 2020), and their use offers advantages in providing suitable combustion (Devarajan et al., 2020); The presence of oxygen in the chemical structure of the fuel increases the respiratory efficiency and thus makes it possible to increase the thermal efficiency of the engine. Also, it can be concluded that with better combustion due to the presence of sufficient oxygen, it converts more of the chemical energy of the fuel into thermal energy.

In the SFM engine, the addition of B5 and B20 together with the TGME additive reduces the BSFC compared to diesel fuel. Due to the low LHV and high density of biodiesel additive (in comparison to diesel), by adding this substance into diesel fuel blends, the combustion process was changed. When using the B5 fuel blend, the BSFC amount was reduced by 16.02% compared to pure diesel fuel. On the other hand, since the BP decreases with increasing the biodiesel amounts in fuel blends (Fig. 6); therefore, this factor also slightly increases the specific fuel consumption compared to TGME additive condition. It is due to prevent engine power loss that leads to increases the fuel consumption; As the biodiesel increases to B20, this BSFC value slightly increases compared to the addition of B5 and the conditions that TGME additive is adding to diesel fuel. It is due to decreases in the BP and thus increases the BSFC (Eq. (3)). By biodiesel B20 with together 0.1 vol.% TGME additive, the BSFC amount was reduced by 11.11% compared to pure diesel fuel. Also, in the study by Elkelawy et al. (2019), the addition of B20 was increased the BSFC; But these values were lower than pure diesel in all conditions. Fig. 8 shows the conditions for using different amounts of TGME additive and biodiesel in SFM and DFM engines. In DFM engines, the reduction in BSFC is more noticeable; this could be due to the decrease in the fuel density (Table 3). Because decreasing the fuel density increases the engine BP (Section 3.1), and this increase in BP reduces the specific fuel consumption. Furthermore, increasing the NG amount could lead to an improvement in the combustion and an increment in the Heat Release Rate (HRR) during the premixed combustion phase (Zhang et al., 2020). In the DFM engine, this amount of the BSFC is less than diesel fuel, and by adding more NG to the fuel blend, this amount is less than diesel fuel; increasing BP is the reason for this condition. Because increases in BP at the DFM engine lead to a reduction of BSFC amount (according to Eq. (3)). Also, according to the Musthafa (2019) study, the DFM engine resulted in a 4.2% reduction in BSFC compared to diesel; therefore, these results were following the results of this study. In general, at the DFM engine, these BSFC values are low; it is due to lower NG density (Table 3) and higher BP in comparison to pure diesel (Fig. 6). The highest reduction in BSFC in comparison to pure diesel was obtained at the DFM engine condition (in NG60 mode) by 0.2 vol% TGME additive. Under these conditions, BSFC was reduced by 33.08% compared to pure diesel fuel.

3.4. Effect of TGME additive, NG, B5, and B20 fuel blends on the BTE

It is important to consider the BTE parameter to check engine performance. High BTE indicates high engine performance. According to Fig. 9, the BTE amount is higher than pure diesel (in all conditions); also, it is higher in DFM than the SFM engine. Increasing the NG amount could lead to an improvement in the combustion, and an increment in the Heat Release Rate (HRR) during the premixed combustion phase (Zhang et al., 2020); this parameter could lead to an improvement in the BTE. In both SFM and DFM engines, adding TGME additive to diesel increased the BTE amount. For conditions that TGME additive used to the fuel blend since the P_{fuel} decreased by adding biodiesel to diesel fuel (due to low fuel mass flow ($\dot{m}_S$)), therefore, the BTE was increased (Eq. (5)). Also, when the biodiesel was added to diesel fuel, the BTE amount was slightly reduced compared to the conditions that the TGME additive added to pure diesel. This result is due to a slight reduction in the BP amount (Section 3.1); by reducing the BP amount, the BTE amount slightly reduces (Eq. (5)). Increased biodiesel (B20) use in diesel fuel blend resulted in a further decrease in the BTE amount compared to the low amount of biodiesel (B5). Also, according to most research, the addition of biodiesel reduced the BTE amount (Sharma and Kaushal, 2020; Madiwale et al., 2018; Tarabet et al., 2014); also, the addition of more biodiesel (B20) to the diesel fuel blend slightly reduced the BTE amount (Elkelawy et al., 2019). But these values were higher than pure diesel in all conditions. According to Fig. 9, when the 0.4 vol% TGME additive is used in diesel fuel blend, the BTE amount is increased by 22.33%, compared to diesel. Also, to investigate the engine performance, it is important to pay attention to the BTE of the engine. The highest increase in BTE compared to pure diesel was obtained at the DFM engine condition (in NG70 mode) by a 0.2 vol% TGME additive. Under these conditions, BTE was increased by 12.77% compared to pure diesel fuel.

3.5. Effect of TGME additive, NG, B5, and B20 fuel blends on the CO emission

CO is one of the substantial pollutants of the diesel engine. The GHG increases are affected by CO emission. The Fig. 10 show that CO emissions in pure diesel mode are higher than other moods; this is due to the lack of oxygen in the structure of pure diesel fuel (Table 3). By 0.3 vol% TGME additive, the CO amount was reduced by 28.74% compared to pure diesel fuel. In the SFM engine, the addition of the TGME additive reduces CO emissions; this can be due to oxygen in the fuel structure. Also, biodiesel contained oxygen; the addition of the oxygenated fuels is appropriate for reducing CO emissions (Devarajan et al., 2020); so, with the addition of biodiesel to the diesel fuel, the CO emission was decreased slightly. By 0.1.vol% TGME additive in the B5 fuel blend, the CO amount was reduced by 3.51% compared to pure diesel fuel. The addition of biodiesel to the compounds of diesel and TGME additive leads to a slightly increased in the CO emissions compared to the blend of diesel and TGME additive. But, in general, adding biodiesel to the SFM engine reduces the CO amount compared to diesel fuel. Also, according to the researches by Hwang et al. (2016), and Saravanan et al. (2020), the addition of biodiesel influenced on reducing the CO emission; the physical properties of the fuel (mostly density and viscosity) was impacted the diesel engine combustion performance. By adding 0.1 vol% TGME additive to the B20 fuel blend, the CO emission reduced compared to diesel fuel by 23.83%.

The B20 conditions were slightly better than the B5, which could be due to the improvement of some combustion properties (due to more oxygen); The presence of oxygen in the chemical structure of the fuel increases the respiratory efficiency and thus makes it possible to increase the thermal efficiency of the engine. Also, it can be concluded that with better combustion due to the presence of sufficient oxygen, it converts more of the chemical energy of the fuel into thermal energy. This better combustion could be reduced the CO emission. Fig. 10 shows the conditions for using different amounts of TGME additive and biodiesel in SFM and DFM engines to reduce CO emission. For all conditions of the DFM engine, the CO emission was highly reduced compared to the SFM engine. Due to the improvement of the fuel properties and combustion process. Because NG fuel has low carbon (Table 3), this factor leads to the reduction of CO emissions. Also, researches by Mofijur et al. (2019), and Kan et al. (2020), reported that the DFM engine strategy was effective in

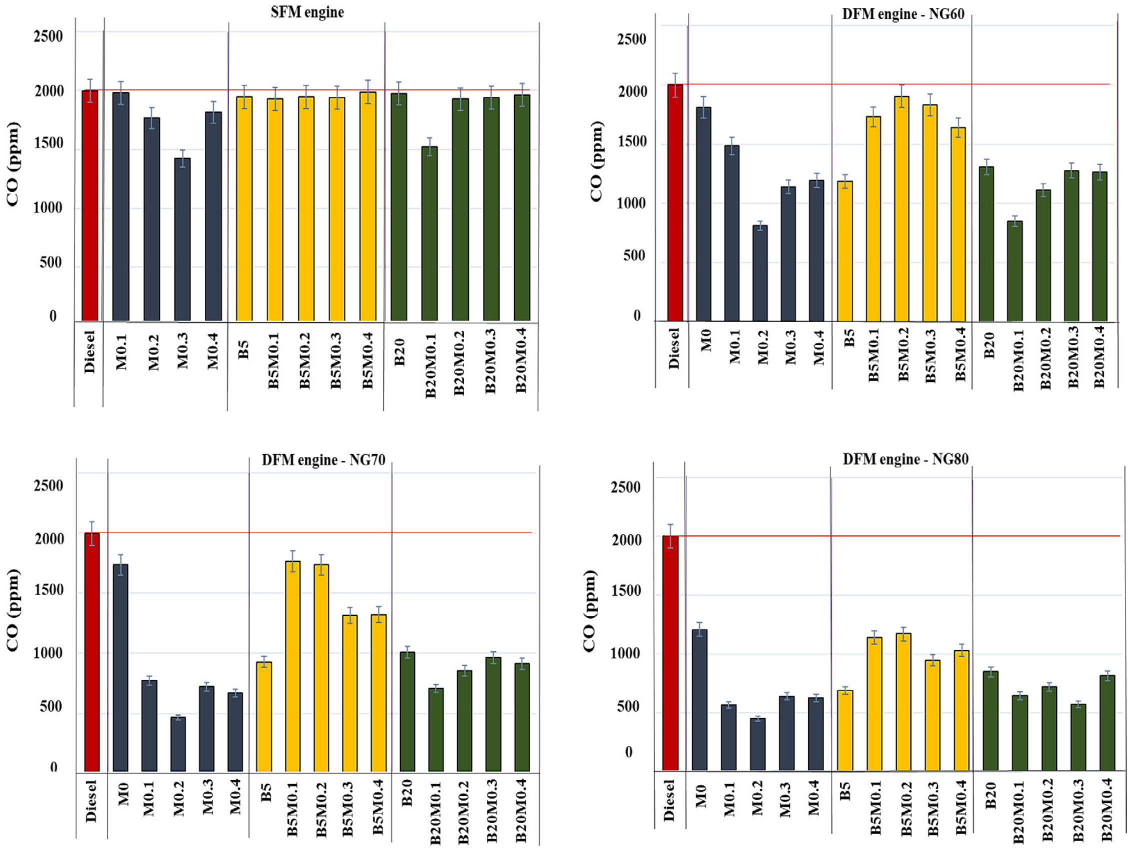

Fig. 10. Effects of TGME additive, NG, B5, and B20 fuel blends on the CO emission.

reducing the emissions; therefore, these results were following the results of this study. Due to increased oxygen content, the addition of the TGME additive at the DFM engine resulted in more CO emissions reduction. Also, the addition of B20 and B5 at the DFM engine reduced the amount of CO emission more than the SFM engine condition. The DFM engine can improve some performance parameters (Kan et al., 2020); also, according to the study by Saravanan et al. (2020), the addition of biodiesel B20 had a suitable effect on reducing CO emission from the DFM engine; therefore, these results were following the results of this study. According to Fig. 10, the highest reduction in CO emissions compared to pure diesel was obtained at the DFM engine condition (in NG80 mode) by 0.2 vol% TGME additive. In these conditions, CO emission was reduced by 77.56% in comparison to diesel fuel.

3.6. Effect of TGME additive, NG, B5, and B20 fuel blends on the CO_2 emission

Another emission of the engine is CO_2, which has a significant impact on environmental pollution. Improving the combustion process depended on improving fuel properties. Therefore, the combustion process and CO_2 emission-quality are affected by any modifications of the fuel formulation characteristics (Ilyas et al., 2014). By 0.2 vol% TGME additive, the CO_2 amount was reduced by 22.72% compared to pure diesel fuel. In the SFM engine, the TGME additive addition reduces the CO_2 emission; this can be due to the fuel properties influences and viscosity reduction (Table 3). The low viscosity of fuel could lead to a decrease in CO_2 emission since diesel engines' fuel injector is not tuned for such a low viscosity (Hazrat et al., 2019). Also, the fuel properties' influence in changing the combustion (Han et al., 2020) and emission process (Imtenan et al., 2015), were pointed in most research. According to Fig. 11, the CO_2 emissions for B5 fuel are higher than pure diesel fuel but for B20 fuel less than diesel fuel. The high cetane number of the biodiesel increases the ignition delay time and can, therefore, provide more time to convert CO to CO_2 (Yildizhan et al., 2017). Fig. 11 shows the conditions for using different amounts of TGME additive and biodiesel in the SFM and DFM engines to reduce CO_2 emission. The CO_2 emission was slightly changed at the DFM engine compared to the SFM engine. Therefore, using NG in the DFM engine at higher percentages to reduce CO_2 emission, could be one of the appropriate methods; also, this result was stated in the research by Di Blasio et al. (2017). According to Fig. 11, the highest reduction in CO_2 emission in comparison to pure diesel was obtained at the DFM engine condition (in NG70 mode) by 0.2 vol% TGME additive. This condition was reduced CO_2 emission by 40.9% compared to pure diesel fuel.

3.7. Effect of TGME additive, NG, B5, and B20 fuel blends on the exhaust gas temperature (EGT)

Exhaust gas temperature is another operating parameter of the engine, which can provide information about the fuel's combustion process. Exhaust gas temperature affects engine emissions. As shown in Fig. 12, in the SFM engine the addition of TGME additive reduces the exhaust gas temperature compared to diesel. According to Fig. 12, it can be seen that the highest amount of exhaust gas temperature reduction at the SFM engine is related to the conditions of adding the TGME additive in the amount of 0.2 vol.% to diesel fuel. In this condition, the exhaust gas temperature reduces to 11.43%, compared to diesel fuel. This may be due to the presence of oxygen in the TGME additive structure; because oxygenated fuels reduce the combustion chamber's temperature (Ancillotti and Fattore, 1998), this factor can reduce the exhaust gas temperature. However, when biodiesel B5 and

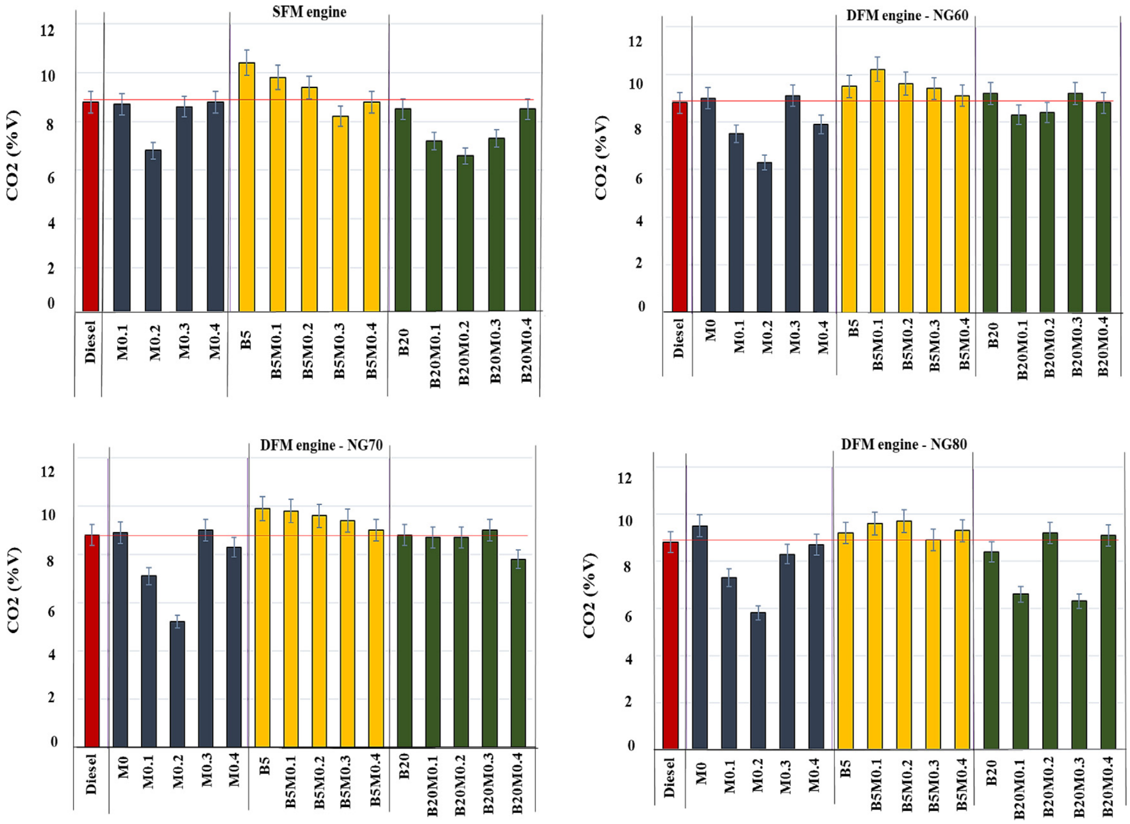

Fig. 11. Effects of TGME additive, NG, B5, and B20 fuel blends on the CO_2 emission.

B20 are added to the fuel blends, the exhaust gas temperatures increase slightly compared to TGME additive condition. The use of biodiesel increased the temperature of the exhaust gases; this is related to changing the physical properties of the fuel (Elkelawy et al., 2019), such as the high density of biodiesel and also its high viscosity can be affecting the temperature of exhaust gases (Table 5), because it changes the process of fuel atomization and fuel combustion.

In the DFM engine, the conditions were similar to SFM engines, although the exhaust gas temperature was slightly higher in some conditions. Also, in the study of Nayak and Mishra (2019), at the DFM engine conditions, the exhaust gas temperature was higher than the SFM engine; therefore, these results were following the results of this study. In general, the addition of a TGME additive further reduces the temperature of the exhaust gases compared to the addition of biodiesel B5 and B20 (Fig. 12). Therefore, in this regard, the addition of a TGME additive can play an important role in reducing other engine emissions.

3.8. Effect of TGME additive, NG, B5, and B20 fuel blends on the NOx emission

The parameter of NOx emission is a combination of nitrogen and oxygen compounds caused by the combustion chamber's high temperature. Due to the high heat of the combustion chamber (Kalsi, 2017), and high exhausted gas temperature, N_2 gas is easily separated. By 0.1 vol% TGME additive, NOx amount was reduced by 43.15% compared to pure diesel fuel. In the SFM engine, the addition of the low percent of the TGME additive improves the NOx emissions. This result may be due to suitable oxygen; because oxygenated fuel reduces the temperature of the combustion chamber and reduces the exhaust gas temperature (Fig. 12), a suitable oxygen amount reduces the NOx emission. But, when oxygenated fuel (Biodiesel and TGME additive) more increases due to the reaction of O_2 with N_2, the NOx emission was increased. The addition of biodiesel B5 with together TGME additive to diesel fuel increases the NOx amount. Also, according to research results by Saravanan et al. (2020), and Jiaqiang et al. (2018), the NOx emission increased by the addition of biodiesel; also, an increase in the amount of biodiesel (B20) in the fuel mixture increased the NOx emission (Singh and Sandhu, 2020); therefore, these results were following the results of this study.

Fig. 13 shows the conditions for using different amounts of TGME additive and biodiesel blends at the SFM and DFM engine for achieving low NOx emission amounts. The increase was observed in the NOx emission at the DFM engine in comparison to the SFM engine. Also, according to the studies of Saravanan et al. (2020), and Kan et al. (2020), the amount of NOx emission slightly increased at the DFM engine mode. This result may be due to the high heat of the combustion chamber, or high EGT amount. Furthermore, increasing the NG amount could lead to an improvement in the combustion, an enhance in the HRR during the premixed combustion phase (Das et al., 2018). This result shows that almost all conditions of NOx emission at the DFM are higher than the SFM engine. By adding 0.3 vol% TGME additive to the B20 fuel blend at the DFM engine (in NG80 mode), the NOx amount was increased by 21.57% compared to pure diesel fuel. But, the only best conditions that NOx emission was obtained lower than pure diesel fuel were achieved by the addition of 0.1 vol.% TGME additive to diesel fuel in SFM engine. In this condition, the NOx emission was reduced by 43.15% in comparison to diesel.

3.9. Effect of TGME additive, NG, B5, and B20 fuel blends on the generated power cost

An economic evaluation of fuel consumption is one of the substantial parameters to determine the best conditions. The cost of diesel, biodiesel B5 and B20 was considered 2.55, 2.51, and 2.49

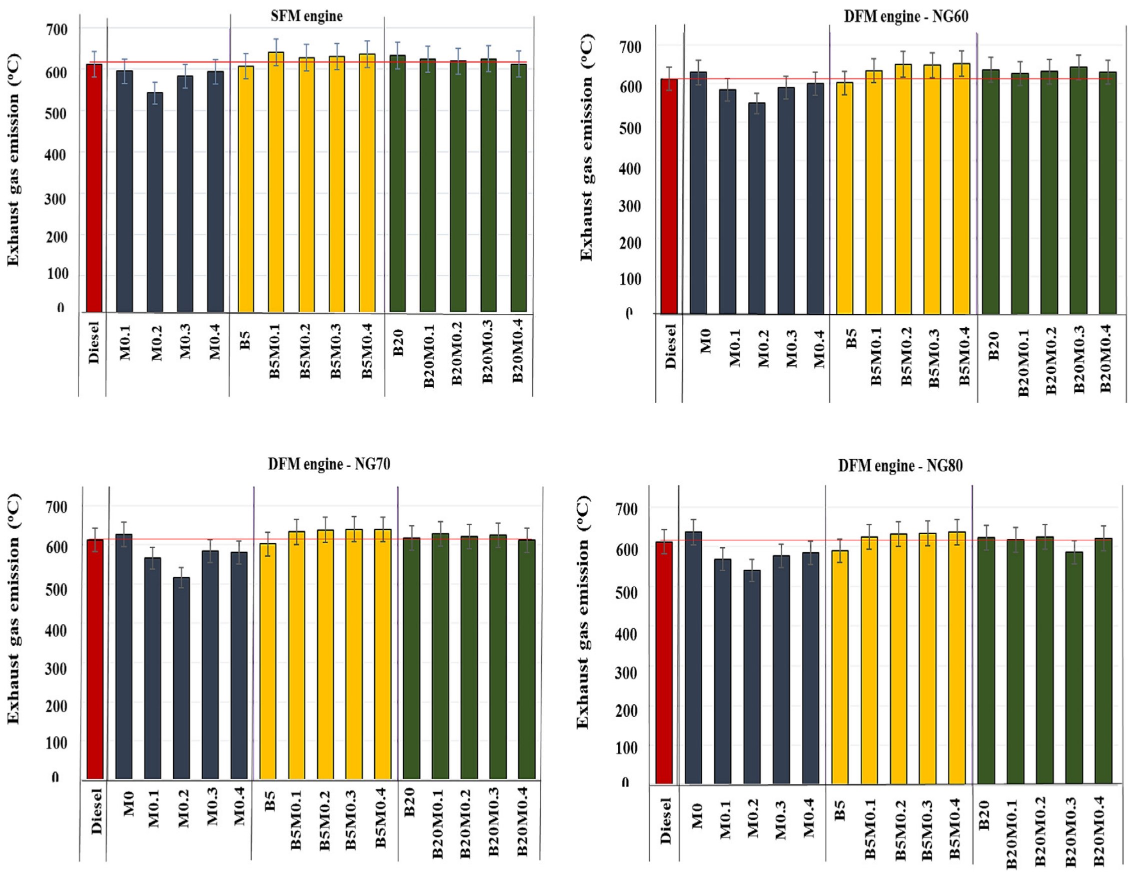

Fig. 12. Effects of TGME additive, NG, B5, and B20 fuel blends on the Exhaust gas temperature.

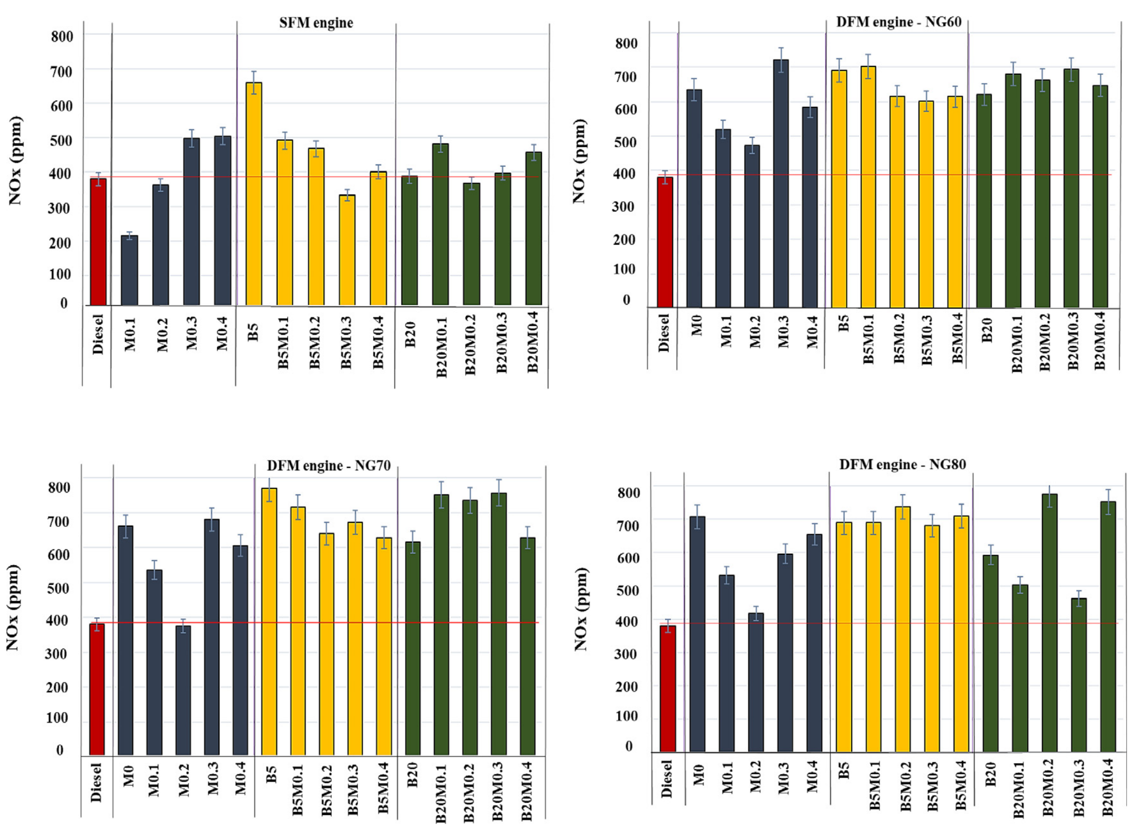

Fig. 13. Effects of TGME additive, NG, B5, and B20 fuel blends on the NOx emission.

\$/gallon, respectively (Bourbon, 2018). The TGME additive was considered 64.581\$/Lit according to the comparison of the similar material from the Merck site. Also, the cost of NG was considered 0.0085 \$/Lit (Akbarian and Najafi, 2019). For each fuel sample, the fuel cost was estimated, then, based on the calculated BP from the dynamometer data, so the amount of generated power cost was obtained in \$/kWh. The generated power cost analysis results were demonstrated in Fig. 14.

In most conditions, biodiesel and TGME additive addition lead to a slight increase in the generated power cost. But it had to evaluate that this increase in generated power cost was acceptable and applicable against engine performance and emissions changes. For the SFM engine, adding 0.2 vol% TGME additive to diesel fuel reduced the generated power cost by up to 1.12% in comparison to diesel. The addition of B20 to diesel fuel reduced the generated power cost by 4.7% in comparison to diesel fuel that would be a useful conclusion. However, adding B5 with TGME additive up to 0.3 vol% would increase the generated power cost to 23.72% compared to pure diesel. Using 0.3 vol% TGME additive into diesel fuel at the DFM engine (in the NG60 mode), reduced the generated power cost by 8.32% compared to diesel; as well as improved performance and emissions. At the DFM engine in NG70 mode by using 0.2 vol% TGME additive in the B20 fuel blend, the generated power cost was reduced to 20.16%. Also, adding 0.4 vol% TGME additive to the B20 at the DFM engine in NG80 mode, reduced the generated power cost to 2.35% compared to diesel. The lower emissions and the higher engine operating condition, with lower generated power costs, is the best condition.

According to generated power cost analysis results, for each of the different SFM and DFM engines' different conditions, the addition of TGME additive into diesel fuel reduced the generated power costs. Also, the use of TGME additive in lower percentages at the DFM engine has had better results in decreasing the generated power cost compared to pure diesel. The highest BTE amount was obtained by 0.2 vol% TGME additive into diesel fuel at the DFM engine with NG70 mode, under these conditions, the BTE amount was increased by 12.77%, and the generated power cost was reduced to 20.16% in comparison to pure diesel. But along with improving the BTE and generated power cost amounts, improvement of other emissions and performance parameters of the engine also should occur; so, it is important to pay attention to all conditions. By considering these parameters, the results demonstrated that most of the parameters also improved with the addition of 0.2 vol% TGME additives to diesel fuel at the DFM engine with NG70 mode. Therefore, this condition with an increase of 12.77% in the BTE amount and a reduction at the generated power cost to 20.16% in comparison to pure diesel, was favorable.

4. Conclusion

Nowadays, the need for new energy sources is one of the major problems for all countries in the world. The use of some alternative fuels requires fundamental changes in engine structure and design. Using renewable energy sources is the best way to improve these conditions. Producing biodiesel from the WCO and managing it to prevent environmental pollution and convert it to biodiesel for diesel engines can be a suitable solution to reduce emissions. Glycerol formed 10% of the biodiesel production process. Excess glycerol has created a new challenge. To further reduce and better manage the environment, the glycerol can convert to a novel fuel additive. Returning it to the fuel cycle is a novel and very viable solution. In this present study, TGME was a novel additive; this additive was obtained from glycerol by the etherification method. One of the advantages of this study was the use of alternative fuel compounds without making major changes to the structure of a conventional diesel engine. The TGME additive was investigated under different percentages at the SFM and DFM engines in various amounts of NG to find suitable conditions for improving engine performance and emissions. The Dual-fuel diesel engine was run under three different high natural gas ratios (60, 70, and 80%), at full-load and 1500 rpm. In summary, the results of this study demonstrated that:

- Glycerol etherification is a good way to convert glycerol to fuel additives and the TGME additive is an important fuel additive. By improving diesel fuel properties through oxygenated additives, engine performance parameters, brake thermal efficiency, and generated power cost can be improved. The addition of the TGME additive into diesel fuel had a very suitable result for SFM and DFM engines, although the generated power costs slightly increased in some modes.
- The presence of O_4 in the chemical structure of the TGME additive can make it a suitable oxygenated additive. Oxygenated fuels contributed to the combustion process and improved it. Also, the TGME additive, due to its appropriate cloud point amount, could solve the biodiesel cloud point problem. Adding this additive at different amounts to diesel fuel has improved the diesel engine's performance and reduce the emissions.
- TGME additive showed better performance compared to other additives (Table 1). Because, compared to the use of di-ethyl ether additive, the TGME additive had better results and improved the BP. Also compared to Ethylene glycol, adding the TGME additive at 0.2 vol% was able to reduce the BSFC by 16.92%. Besides, the TGME additive compared to the Dimethyl ether had better results; because unlike these additives, the addition of TGME into diesel fuel leads to the BP increased (up to 1.07%), as well as the BSFC reduced (up to 16.92%) in comparison to diesel fuel. Many types of research need to be done on the extraction of various additives from glycerol, to manage the production of glycerol and reduce environmental problems.
- The use of glycerol-derived oxygenated additives along with a combination of NG and diesel fuels was able to improve combustion conditions. By using this additive in the composition of diesel, the required amount of oxygen was provided in the combustion process and this improved the combustion process and the brake thermal efficiency. The use of this additive with together to NG fuels reduced the emission of carbon pollutants and reduces NOx emissions due to decreasing the temperature of the exhaust gases. Therefore, to improve the properties of fossil fuels, the production of various oxygen additives from glycerol and their study in diesel fuel composition is recommended.
- DFM engine can be one of the positive ways for improving engine performance and emission parameters. Also, using high amounts of NG in diesel engines demonstrated the best engine performance and emission results.
- The lower emissions and the higher engine operating condition is the best condition. Of course, choosing the best modes depends on the parameter that we want to improve. But in this present study, we are looking for the selection of the best operating conditions in terms of low emissions and high engine performance, along with the low generated power cost. By examining the results, this condition obtained with the addition of 0.2 vol% TGME additive into diesel fuel at the DFM engine with NG70 mode;
- Under this condition compared to diesel fuel: The amount of BP increased by 10.54%; also, BSFC and φ decreased by

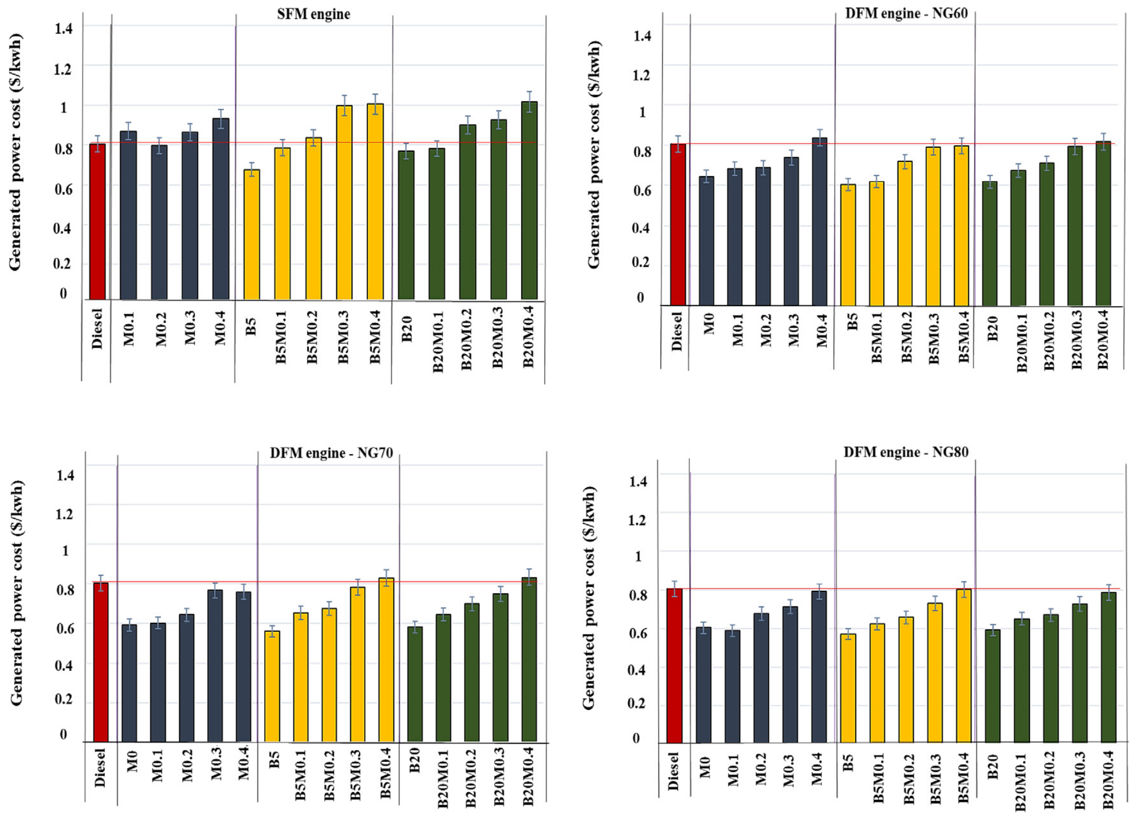

Fig. 14. Effects of TGME additive, NG, B5, and B20 fuel blends on the generated power cost.

33.08 and 8.34%. Besides, CO, CO_2, NOx, and EGT emissions decreased by 76.77, 40.9, 1.31 and 15.71%, respectively. Finally, the amount of BTE increased by 12.77%, as well as the generated power cost was decreased by 20.16%.

The results showed that this condition could improve most engine performance conditions and reduce emission. This result was great because it shows that only by adding TGME additive into the diesel fuel and using the high NG amount at the DFM engine, this best condition achieved; therefore, the use of the TGME additive in these conditions recommended as a suitable solution.

CRediT authorship contribution statement

Farid Haghighat Shoar: Writing - original draft, Investigation. **Bahman Najafi:** conceptualization, supervision, investigation, project administration. **Amir Mosavi:** validation, review, proofreading.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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