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Original Research Article

# Performance and Emission Characteristics of a Diesel Engine Fuelled with Emulsified Biodiesel-Diesel Fuel Blends

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## Abstract

In this study, effects of emulsified fuels on the performance and emissions of a diesel engine were investigated experimentally. Effective power, specific fuel consumption and thermal efficiency as well as emissions of carbon monoxide, hydrocarbon, nitrogen oxide and carbon were considered as parameters for the investigation. Two emulsified fuels, namely B20W10 and B20W15, containing 10 and 15% water by volume, respectively, were prepared by using diesel fuel-biodiesel blend (B20). The emulsified fuels were tested in a naturally aspirated, direct injection diesel engine at partial load conditions. The test results obtained from the emulsified fuels were compared with those of neat diesel fuel and B20. It was found that the emulsified fuels yield higher specific fuel consumptions, while they cause only slight changes in thermal efficiency. The emulsified fuels are very capable of reducing NOx emission at all engine loads. On the other hand, the use of emulsified fuels brings about significant increase in CO and HC emissions at low engine loads, while they cause moderate CO and HC emissions at high engine loads.

**Keywords:** Emulsified fuel; biodiesel; diesel engine; engine performance; exhaust emissions

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## 1. Introduction

The researches on alternative fuels, accelerating with the influence of the petroleum crisis of past years, have been performed extensively. The applications of alternative fuels and fuel systems are required due to many factors such as limited oil resources and restricted exhaust emission values implemented by the legislations.

Among the alternative engine fuels used in diesel engines, biodiesel comes into prominence because of its some superior characteristics. Especially high cetane number and oxygen content make it suitable fuel for use in diesel engines. As a renewable alternative fuel, biodiesel can be produced from vegetable oil as well as waste oils and animal fats [1,2]. So, it has made a significant contribution to the alleviation of environmental problems. It can be supplied to the diesel engine as different ratio of blends with diesel fuel or pure form. It is stated in an experimental study that lubrication capability of biodiesel is better than that of diesel fuel [3]. Ignition delay period has been decreased with the use of biodiesel owing to its high cetane number and better combustion characteristics [4,5].

As a result of experimental studies, it is declared that smoke emission, produced in high amounts in diesel engines, is lower with the use of biodiesel or its blends [6]. Additionally, reductions in CO and HC emissions with the use of biodiesel blends are revealed [7,8]. In terms of greenhouse gases which cause global warming, biodiesel usage has important advantage with the capability of reduction in lifecycle $CO_2$ emissions compared to diesel fuel [8]. However, increase in NOx emissions usually occurs with use of biodiesel compared to diesel fuel because of the effect of oxygen content and better combustion characteristics [9-13].

Due to higher combustion temperature, diesel engines produce higher amounts of NOx emissions when compared with gasoline engines. It is reported that the use of emulsified fuel, consisting with water addition to diesel fuel, is an effective method for NOx emission reduction in diesel engines [14-18]. Furthermore, it is possible to decrease smoke emissions through emulsified fuel usage [19,20]. The use of emulsified fuel in diesel engines causes an increase in ignition delay period compared to diesel fuel [21]. In the literature, there have been studies related with the application of emulsified fuels produced from diesel fuel. A limited number of studies related with emulsified fuel produced from biodiesel have been carried out.

As a result of the performance and emission tests with biodiesel, diesel fuel-biodiesel blend containing 20% biodiesel by volume (B20) have been observed favorable particularly in terms of thermal efficiency [22,23]. Besides, the advantage of B20 comes into prominence among the biodiesel blends when fuel production quantity and production potential are considered. In this study, the effects of emulsified fuels prepared with using diesel fuel-biodiesel blend on the performance and exhaust emissions of a diesel engine were experimentally investigated. For this purpose, oil-in-water-in-oil O/W/O emulsions including 10% and 15% water were prepared and tested in a diesel engine as well as diesel fuel and B20 at partial load conditions. B20 was preferred in the preparation of the emulsified fuels due to some evident reasons as stated above.

## 2. Materials and Method

Biodiesel used in the engine tests was produced via transesterification method. Soybean oil, potassium hydroxide (KOH), and methyl alcohol ($CH_3OH$) were used, and the transesterification method was employed for production of the biodiesel [24]. Diesel fuel was provided by a local gas company. Main properties of the test fuels are given in Table 1.

The employed emulsification process is briefly as follows; Pure water and Tween 80 were blended, and then some B20 was added to this mixture. The mixture was added to a vessel containing another blend which was prepared by mixing process with Span 80 and B20. Thus, after the mixing procedure, three phase emulsion was obtained. Isopropanol and isobutanol were added to improve stability of the emulsion.

Table 1 Main properties of diesel fuel and biodiesel

| **Properties** | **Diesel Fuel** | **Biodiesel (SME)** |
|---|---|---|
| Kinematic viscosity ($mm^2/s$) (at 40 °C) | 2.0─4.5 | 5.57 |
| Specific gravity (at 15 °C) ($g/cm^3$) | 0.82─0.86 | 0.8859 |
| Net heating value (MJ/kg) | 42.7 | 37.034 |
| Cetane number | 46 | 51 |
| Flash point (°C) | 55 | 208 |
| Oxygen content (%) | – | 11.5 |

Two different kinds of emulsified fuels, which contain 10 and 15 % water in volume, were prepared by applying emulsification method. The emulsified fuels, which were prepared using diesel fuel-biodiesel blend (B20), are denoted by B20W10 and B20W15.

The performance and emission tests were performed in a single cylinder, direct injection diesel engine with using B20W10 and B20W15 as well as diesel fuel and B20. The main specifications of the diesel engine are given in Table 2.

Table 2 The specifications of the test engine

| Made | Superstar |
|---|---|
| Cylinder number | 1 |
| Type | Four stroke, direct injection, water cooled, Naturally aspirated |
| Bore | 108 mm |
| Stroke | 100 mm |
| Compression ratio | 17 : 1 |
| Rated power | 16 HP |
| Injection pressure | 171 bar |
| Injection timing | 28° BTDC |

**Table 3** The properties of the exhaust gas analyser

| **Emission** | **Measurement range** | **Measurement accuracy** |
|---|---|---|
| HC (ppm) | 0 – 20000 | ± 12 ppm |
| CO (%) | 0 – 15 | ± %0.06 |
| $CO_2$ (%) | 0 – 20 | ± %0.5 |
| NO (ppm) | 0 – 2000 | ± 5 ppm |

As seen from Fig.1, the experimental set up consists of a diesel engine, an electrical dynamometer, measurement system for fuel consumption, measurement system for air consumption and thermocouples for temperature measurements at different points. An electrical dynamometer was coupled to the test engine to determine brake torque and load the diesel engine. There are a load sensor and a speed sensor on the dynamometer. Mass flow rate of the test fuels were measured by using a computer controlled, electronic scale having precision of 0.1 g. Exhaust gas emissions of NO, HC, CO and $CO_2$ were measured by a MRU Delta 1600 L exhaust gas analyzer. The properties of the exhaust gas analyzer are given in Table 3. Temperatures of the cooling water entering and leaving the test engine were continuously controlled via K type thermocouples. Thus, engine operating temperature was maintained at constant value. Besides, ambient temperature during the test was measured with a thermocouple. The tests were performed at the constant speed-variable load conditions. Therefore, the diesel engine was operated at 1400 rpm and various engine loads (between 20% and full load). The diesel engine was warmed up before the measurements. First, the test was carried out with diesel fuel, and then the same test procedure was repeated with using B20 and emulsified fuels.

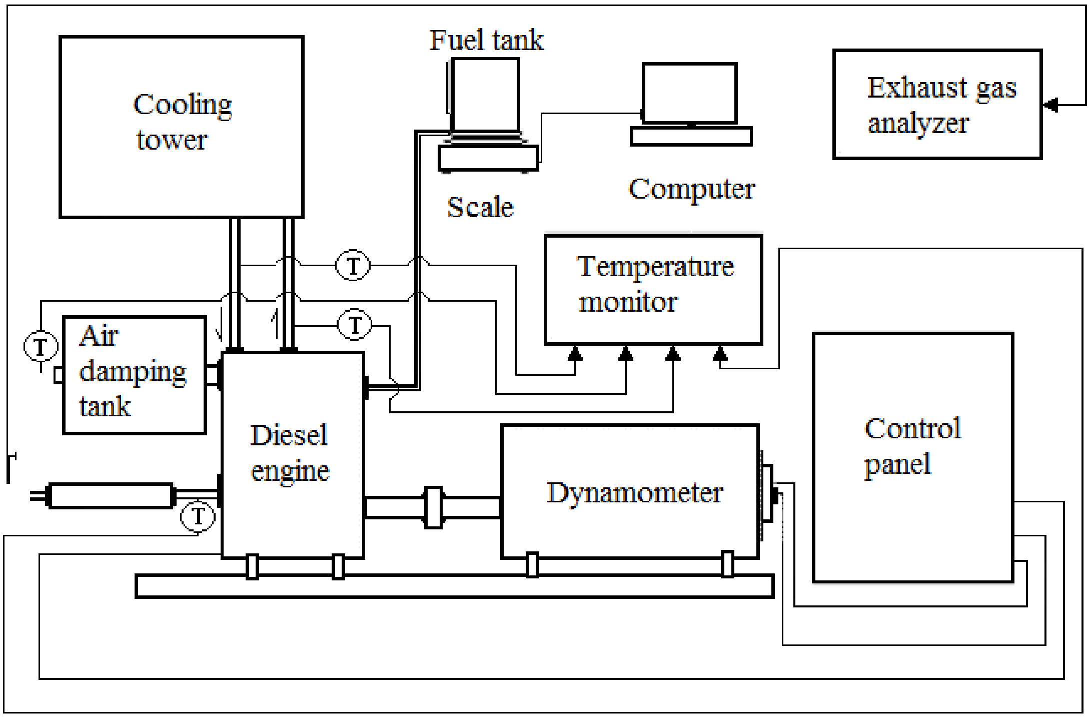


**Fig. 1** Experimental setup

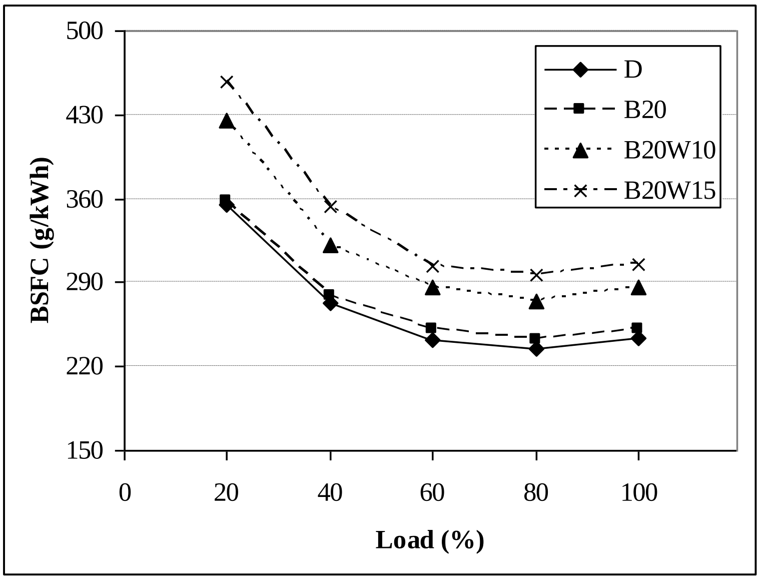


**Fig. 2** Brake specific fuel consumption

## 3. Results

There was no problem encountered in the tests at different conditions with use of the emulsified fuels as well as diesel fuel and B20. After the experiment of the test fuels, the finding concerning with engine performance parameters and exhaust emissions are given below.

### 3.1. Brake specific fuel consumption

The variations of break specific fuel consumption (BSFC) with the use of diesel fuel, B20, B20W10 and B20W15 as a function of engine load are given in Fig. 2. BSFC values decrease depending on the the increase in the engine load with all the test fuels. But, BSFC values tend to increase slightly at full load condition. There is no distinctive difference in BSFC values with the use of diesel fuel and B20. However, BSFC values obtained from the emulsified fuels are higher than those from diesel fuel and B20. Calorific value of a fuel is known as an important factor for BSFC variation. The water content of the emulsified fuels causes a decerase in the calorific values, and it can be regarded as a main reason for the BSFC increase. Maximum BSFC values are determined with B20W15 which has higher water content. Water content of the emulsified fuels reduces the calorific value of the fuel which is injected into the cylinder. So, more fuel is required with emulsified fuels to get the same power obtained with diesel fuel, thus causing higher BSFC values.

### 3.2. Brake thermal efficiency

As seen from Fig. 3, the brake thermal efficiency (BTE) values increase slightly with the use of B20 in comparison to diesel fuel. Oxygen content of biodiesel and improvement in combustion characteristics are the main reasons for the BTE increase with B20. BTE values of emulsified fuels do not change significantly in comparison to those of diesel fuel. But, a slight decrease in the BTE values is observed when the average values are taken into account. BTE values are closer to each other with the use of B20W10 and B20W15.

In spite of the water content, moderate change in the BSFC values with the use of emulsified fuels can be recognized as a favorable matter. The water content of the emulsified fuels leads to more improvement in fuel-air mixture formation and moderate level BTE values.

### 3.3. CO emissions

CO emissions are lower with B20 in comparison to diesel fuel. However, CO emissions of emulsified fuels increase compared to diesel fuel for the operations at low and medium engine loads, as shown in Fig. 4. Lower in-cylinder temperatures, which are experienced especially at low and medium engine loads, are the main reason of this increment in CO emissions. It is reported that ignition delay period of the combustion process is extended by using emulsified fuel [20,21]. As a result of fuel injection into the cylinder, the water content of emulsified fuel absorbs more heat from in-cylinder of the engine for evaporation. Hence, in-cylinder temperature levels decrease and ignition delay period extends with the emulsified fuels. Also, it is known that the fuel consumption value is usually higher at lower engine loads. Consequently, CO emission formation increases due to elongation of the combustion process at this engine loads.

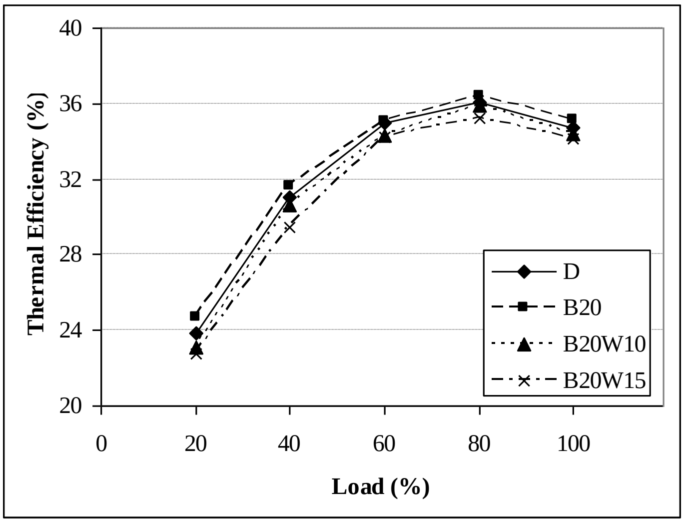


Fig. 3 Thermal efficiency

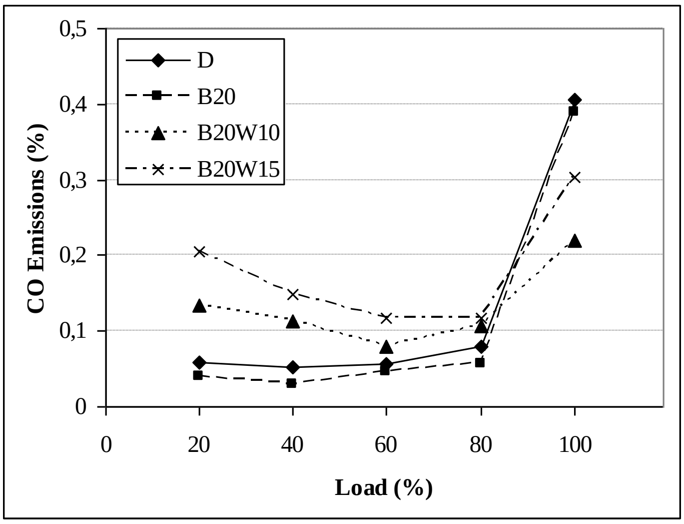


Fig. 4 CO emissions

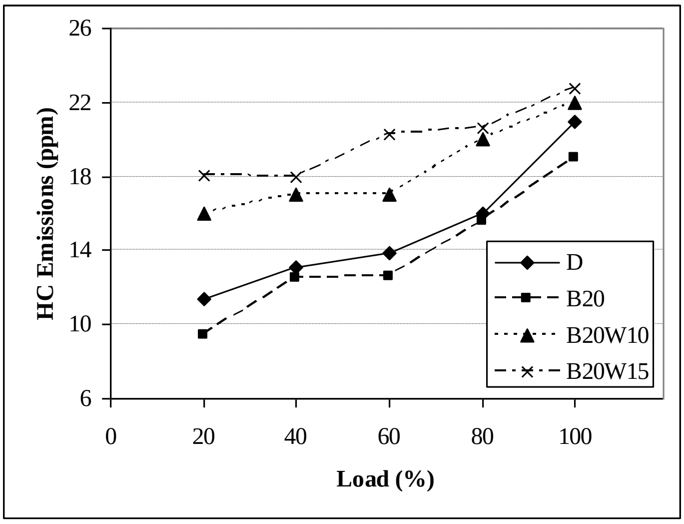


Fig. 5 HC emissions

Besides, for the operation at full load conditions, there is some reduction in CO emissions with emulsified fuels in comparison to diesel fuel. This reduction may be attributed to the mixture formation improvement at the higher engine loads because of the increase in the in-cylinder temperature levels and air turbulence, which cause diminishing effect in ignition delay period. Thus, the heat needed for evaporation of the emulsified fuels is compensated and CO emission formation reduces. There are significant increases with all the test fuels in CO emissions for the operations at full load condition owing to the increase in fuel consumption and decline at A/F ratio.

### 3.4. HC emissions

The variations in HC emission associated with the engine loads for diesel fuel, B20 and emulsified fuels can be seen in Fig. 5. Slightly lower HC emission values are observed with the use of B20 compared to diesel fuel. Besides, HC emissions with emulsified fuels are significantly higher under the operation at low engine load conditions in comparison to those with diesel fuel. Hovewer, by increment of the engine load, HC emission values with emulsified fuels tend to get closer to those with diesel fuel. It is a fact that vaporization heat of water is higher than those of biodiesel and diesel fuel. So, emulsified fuels absorb more heat for evaporation from in-cylinder of the engine due to the water content, which leads to an increase in the flame-quench effect and deteriorate in HC emissions at the low engine load condition. By the engine load increment, the flame-quench effect alleviates owing to the in-cylinder temperature increase. Also, mixture formation of air-fuel improves because of water content of the emulsified fuel at this condition, As a result of the effects mentioned above, HC emission values of the emulsified fuels get closer to that of diesel fuel at high engine loads. As it can be seen, HC emission values of B20W15 are higher than that of B20W10.

### 3.5. NO emissions

As seen in Fig.6, NO emissions increase for all the test fuels with increasing engine load. NO emission values of B20 are higher than those of diesel fuel. This difference can be explained as the effect of biodiesel addition, which reduces ignition delay period of combustion process. Besides, there is a significant decrease in NO emissions with the use of emulsified fuels. Water content of the emulsified fuel reduces maximum combustion temperature due to its higher vaporization heat. So, the emulsified fuels cause some decreasing trend in the formation of NO emission. The reduction in NO emission values appears as more distinctive with the increase of water ratio in emulsified fuels. Also, this reduction is observed at low and medium loads as well as high engine load. It is revealed that ignition delay period of mixture extends, and start of combustion process is delayed with the use of emulsified fuels at low engine loads [20]. As a result, NO emission values decrease with the use of emulsified fuels due to the prolonged combustion process. Depending on the water content, the lowest NO emission values are achieved with B20W15 fuel among the test fuels.

### 3.6. $CO_2$ emissions

As a common trend, $CO_2$ emission values increase for all the test fuels with the increment of engine load due to the increased fuel consumption as shown in Fig. 7. C/H ratio of fuels and completion of combustion process are regarded as significant factors for $CO_2$ emission formation in internal combustion (IC) engines. Due to the effect of combustion improvement of B20, there are slightly increase in $CO_2$ emission values in comparison to diesel fuel at all engine loads. Besides, $CO_2$ emission values with the use of emulsified fuels are slightly lower in comparison to B20 and diesel fuel. The water content of the emulsified fuels can be attributed to the main reason for this reduction.

### 3.7. Exhaust gas temperatures

Exhaust gas temperatures usually increase with increment of engine load due to the increase in fuel consumption, and they reach the maximum values at full load conditions. As it can be seen in Fig. 8, exhaust gas temperatures decrease with other test fuels in comparison to diesel fuel.

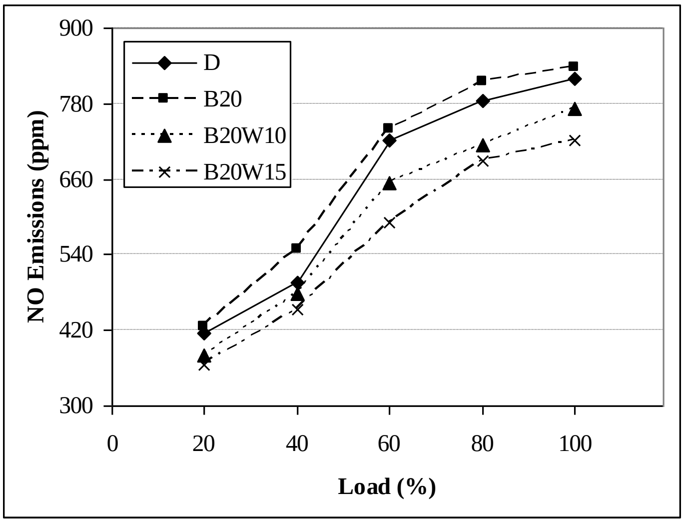


Fig. 6 NO emissions

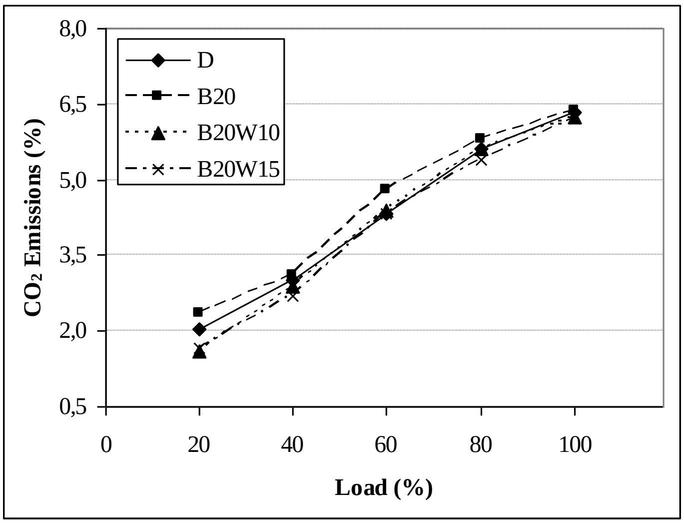


Fig. 7 $CO_2$ emissions

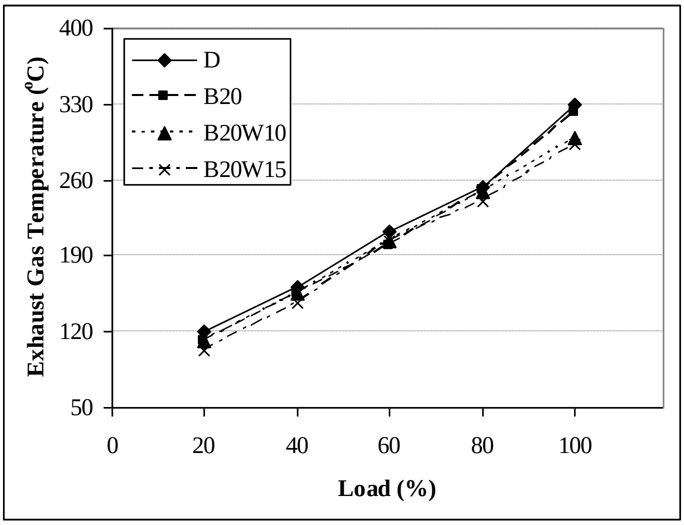


Fig. 8 Exhaust gas temperature

Because of oxygen content and high cetane number, biodiesel blend improves combustion process and cause low exhaust gas temperatures in comparison with diesel fuel. Furthermore, use of the emulsified fuels leads to lower exhaust gas temperatures due to their lower calorific value and higher vaporization heat. The water content of the emulsified fuel leads to the absorbtion of more heat from in-cylinder of the diesel engine. Thus, the exhaust gas temperatures decrease. The exhaust gas temperatures change depending on the water content of the emulsified fuels. Thereby, the lowest exhaust gas temperatures are obtained with B20W15.

## 4. Conclusions

1) There occurred no problem with the use of emulsified fuels during the engine tests.

2) There is an increase in BSFC values with the use of emulsified fuels in comparison to diesel fuel. The increase in the BSFC values depends on water content of the emulsified fuel, and the highest BSFC values are determined with use of the 20W15.

3) BTE values were slightly lower with the use of emulsified fuels in comparison to diesel fuel and B20. Besides, BTE values are close to each other with using of B20W10 and B20W15

4) At low engine loads, higher HC emission values are experienced with the emulsified fuels in comparison to diesel fuel. However, HC emission values with the emulsified fuels indicate an approaching trend to those with diesel fuel due to the improved combustion conditions. In addition, CO emissions increase with the use of emulsified fuels at

low-medium loads but they especially diminish at full load condition.

5) Owing to influence of the water content, lower exhaust gas temperatures are observed for emulsified fuels. In addition, $CO_2$ emission values are lower with emulsified fuels in consequence of the water content.

6) It is revealed that emulsified fuel usage is significantly effective on the reduction of NO emissions. Also, NOx emission reduction occurs with the use of emulsified fuels at all loads. The higher water content causes lower NO emissions. Hence, B20W15 produces the lowest NO emissions among the fuels tested.

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