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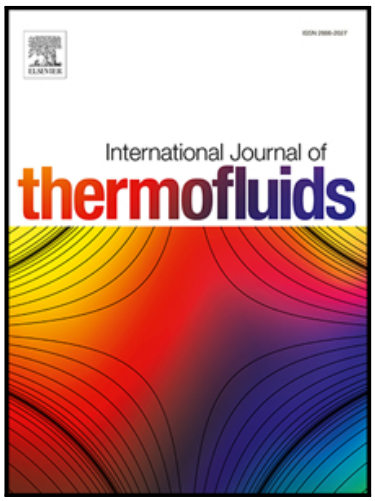

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Investigation of the effect of utilisation of nano boron, diesel and biodiesel fuels with together hydrogen in a compression ignition engine on combustion characteristics

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ABSTRACT

Compression ignition (diesel) engines are the most important element of transportation. Efficiency is a vital factor in diesel engines in terms of environmental protection and sustainability. Therefore, increasing the efficiency of diesel engines by using various additives is an important research topic. In this context, 8 different fuel types were created by adding 10% biodiesel, 50ppm nanoboron (nanoboron particle size 20 nm) and hydrogen (18% of the energy consumption of Diesel/B10 fuels was replaced) to diesel fuel in the current study. A heavy-duty diesel engine was operated at a constant engine speed of 650 rpm and a torque of 200 Nm using these eight fuel types. As a result of the experiments, diesel fuel with 50ppm nanoboron added produced the highest efficiency among all fuel types with a thermal efficiency value of 28.837%. In the experiments carried out with standard diesel (D) fuel, when the thermal efficiency values obtained were compared with D_50ppmB and D_H2 fuels, an efficiency increase of 1.95% and 0.19% was achieved, respectively. On the other hand, when compared with B10_50ppmB, B10_H2, B10, B10_50ppmB_H2 and D_50ppmB_H2 fuels, an efficiency decrease of 0.99%, 2.66%, 2.75%, 3.53% and 5.38% was attained, respectively. 50ppm nano boron addition to pure diesel increased the NO emission rate by 3.15%. On the contrary, a significant decrease was observed in NO emission when hydrogen was used with all fuel types. For example, the NO emission value, which was 3.62 g/kWh in the use of pure diesel, decreased by 32.6% and dropped to 2.44 g/kWh in the D-H2 mixture. In addition, it was observed that the NOx emission value, which was 3.60 g/kWh when B10 (90% diesel + 10% biodiesel) fuel was used, decreased by 29.72% to 2.53 g/kWh when B10_H2 fuel was used. The most important findings of this study are that the nanoparticle additive increased thermal efficiency and reduced CO emissions. In this study, the

combustion of diesel, biodiesel, hydrogen and nanoboron fuels in various combinations was investigated. It is thought that this quaternary fuel mixture significantly contributed to the literature.

Keywords: Nanoparticle Boron, Hydrogen, Diesel, Biodiesel, Combustion.

INTRODUCTION

In the modern world, energy production is essential. It is a major component of modern life, powering everything from the cars we drive to the electricity that lights our homes. Fossil fuel burning accounts for about 82% of the world's energy supply [1] and the industrialization of nations is still powered mainly by these energy sources. Fossil fuels, on the other hand, are non-renewable resources since they cannot be replenished once they are depleted. Furthermore, fossil fuels are the main source of greenhouse gas emissions that harm the environment and human health in addition to contributing to climate change. GENEVA (30 November 2023): UN human rights experts warned of the enormous extent of fossil fuels' detrimental effects on human rights, and they encouraged States to expedite the just and equitable phase-out of these fuels. Even today, fossil fuels continue to be widely recognized as the main source of greenhouse gas emissions, which are directly responsible for the climate crisis. [2]

Nomenclature

BSEC	Brake Specific Energy Consumption	**CO**	carbon monoxide
BSFC	Brake Specific Fuel Consumption	**CO_2**	carbine dioxide
BTE	Brake Thermal Efficiency	**HC**	hydro carbon
Nm	Newton meter	**NO_x**	nitrogen oxides
nm	Nanometer	**LHV**	Lower Heating Value
g	gram	**LHV_K**	lower heating value of mixed fuels
mm	millimeter	**$\dot{m}$**	mass flow
P_b	Brake power	**rpm**	revolution per minute
min.	minute		
ppm	Parts per million		
kWh	kilowatt-hour		

The current concern, not only on the decrease of fossil fuel resources, but also on the environmental problems associated with the combustion of these fuels to generate energy has triggered researchers to invest efforts in alternative fuels that are eco-friendly. Reducing the consumption of fossil fuels is one of the best strategies for lowering GHG emissions [3–4]. Creating engines that are Powered by Carbon-free fuels may be seen as the best way to solve this problem. But this could be a very long-term plan. It may take a long time before completely carbon-neutral vehicles are in service worldwide. Moreover, these fully green fuels, for example, powered by a battery, can not supply sufficient power to work existing strong diesel engines and heavy-duty vehicles (HDV), such as

marine engines. Therefore, (1.)increasing thermal efficiency (BTE) and (2.)replacing hydrogen with part of carbon-based fuels may be the best solution to reduce GHG emissions in current diesel and HDV engines.

If we need to focus on the first of these two items, which is seen as a more applicable solution in the short term, adding a certain amount of biodiesel and nanoparticles to diesel fuel to increase thermal efficiency is a good suggestion. Greenhouse gas emissions decrease as less fossil fuel is utilized in conjunction with biofuels [12, 14]. Pure vegetable oils, ethanol, and biodiesel have recently been seen as reasonable and promising biofuels in this regard [15–17]. However, the high production of NOx, which results in poor combustion performance, is a limitation for both diesel and biodiesel fuels [18–20]. Pure biodiesel has additional downsides as well, which include high viscosity, issues with atomization and spray, a lower heating value, and cold flow characteristics. Fuel additives are therefore receiving a lot of research in an effort to improve the oxidation properties of biodiesel and get around these limitations. Blending these fuel additives with diesel or biodiesel could enhance combustion and successfully lower greenhouse gas emissions. Nanofluid has the potential to be a viable fuel additive option because of its thermo-physical properties, heat transfer rate, catalyst reactivity, and fuel mixture stabilization [21–26]. A nanofuel is a base liquid fuel that contains nanoscale particles, such as iron, aluminium, boron, and their compounds, suspended in it [27]. Tests on fuel properties by adding different types of nanoparticles in various diesel/biodiesel fuels have been carried out by researches in the field [25, 28-39]. In the literature, experiments have shown the varying outcomes that can be obtained when using different types of nanoparticles in various diesel/biodiesel blends. Pourhoseini et al [65] conducted alternative fuel research by adding iron (Fe) nanoparticles (35 - 40 nm particle size, additive amount 500 ppm) to a mixture of pure diesel and 20% biodiesel. They reported that the iron nanoparticle additive reduced fuel consumption. In addition, they stated that while CO emissions improved, NO emissions increased. Wu et al [66] mixed standard diesel, 10% biodiesel and 4% ethanol with 30 ppm carbon-coated aluminium nanoparticles (60 - 160 nm particle size). They achieved 6% fuel savings with this quadruple mixture. Firew et al [67] conducted experiments by adding nickel, zinc, and iron oxide triple additive to a diesel and ethanol liquid-liquid mixture. They added nanoparticles in the amounts of 25, 50, 75 and 100 ppm. They observed improvements in power output with nanoparticle additives. They also reported that thermal efficiency increased. Hoang et al [68] used cerium oxide nanoparticle additive to overcome the properties of biodiesel, which adversely affect fuel atomization, such as high molecular mass, high viscosity and low calorific value when biodiesel is used together with diesel fuel. It was stated that the addition of nano cerium oxide to the biodiesel-diesel mixture improved the combustion characteristics. As a result, a decrease in BSFC was observed. In addition, a significant decrease in CO, HC and smoke emissions was reported. Nour et al [69] used aluminium oxide (25 - 50 nm particle size, 25 - 50 - 75 -100 ppm in quantity) in diesel and biodiesel mixtures. According to the study; nanoparticle additive to the Diesel-Biodiesel mixture overcomes the properties of biodiesel that adversely affect thermal efficiency and increase thermal efficiency. Therefore, brake-specific fuel consumption is reduced. In

addition, the authors reported that CO emission was improved with nanoparticle additives, while NO emission increased. Venu et al [70] used aluminium oxide additives with 28-30 nm particle size in diesel, biodiesel and ethanol liquid fuel blends. They reported that low fuel consumption was achieved with nanoparticle additives. They also encountered higher NO emissions while lower carbon dioxide and smoke emissions were obtained. Nanthagopal et al [76] used titanium oxide and zinc oxide nanoparticles (50-100 ppm as an additive amount) in biodiesel-diesel blends. They reported improvement in BSFC and CO emissions. Gad et al [77], Bazdidi et al [78], Kumar et al [79] and Ghanbari et al [5] used aluminium oxide nanoparticle additives in diesel-biodiesel blends and obtained results in line with other studies.

Secondly, hydrogen substitution is a solution to reduce the emissions of fossil fuels. Krishna et al [6] conducted experiments with diesel, biodiesel and hydrogen fuels. They reported that they achieved higher brake thermal efficiency as a result of the experiments with 20% Biodiesel-Diesel and hydrogen dual fuel mode. They reported that they observed an increase in NO emissions while a decrease in HC and CO emissions was observed. Uludamar et al [7] conducted experiments using diesel fuel containing 20% Biodiesel and hydrogen together. As a result of the experiments, it was reported that while thermal efficiency decreased in diesel fuel containing biodiesel, hydrogen aspiration compensated for the decrease in thermal efficiency. Serin et al [8] conducted alternative fuel research using biodiesel and hydrogen fuels. According to their studies, hydrogen reduces fuel consumption. Although a decrease in CO and CO2 emissions was observed, an increase in NO emissions was observed. Yousufuddin et al [9] conducted experiments using diesel, biodiesel and hydrogen fuels together. As a result of the experiments, hydrogen aspiration to 20% biodiesel-added fuel improved thermal efficiency. Although there was a decrease in HC emissions with hydrogen addition, an increase in NO emissions was observed.

In this study, eight different fuel types were created with different combinations of standard diesel, biodiesel, nanoboron and hydrogen fuels. These fuel types were tested in a 6-cylinder, 11670 cc, compression ignition heavy-duty diesel engine at 200 Nm torque and 650 rpm engine speed. The characteristics of quadruple fuel combustion were investigated. Studies on quadruple fuel types are relatively few in the literature. The existing ones need to be strengthened with more experiments. It is thought that this study will help to close this gap in the literature.

1. METHODOLOGY

1.1. Experimental Process

In this study, experiments were conducted with a triple mixture of diesel, biodiesel and hydrogen fuels. In order to investigate the effect of nanoparticle additives on engine performance and exhaust emission values, 50 ppm nano boron with a size of 20 nm was added to liquid fuel mixtures as an additive. The experiments were carried out under an engine load of 200 Nm and an engine speed of 650 rpm. Considering the literature review mentioned in the introduction, the focus was on the 50 ppm amount

[66, 67, 69, 76]. In addition, another factor in choosing 50 ppm boron amount as nanoparticle is that in a previous study conducted in the same test setup [40, 41], the amount of nano boron that increased the efficiency the most was 50 ppm. Therefore, 50 ppm nano boron additive was preferred in this study as well.

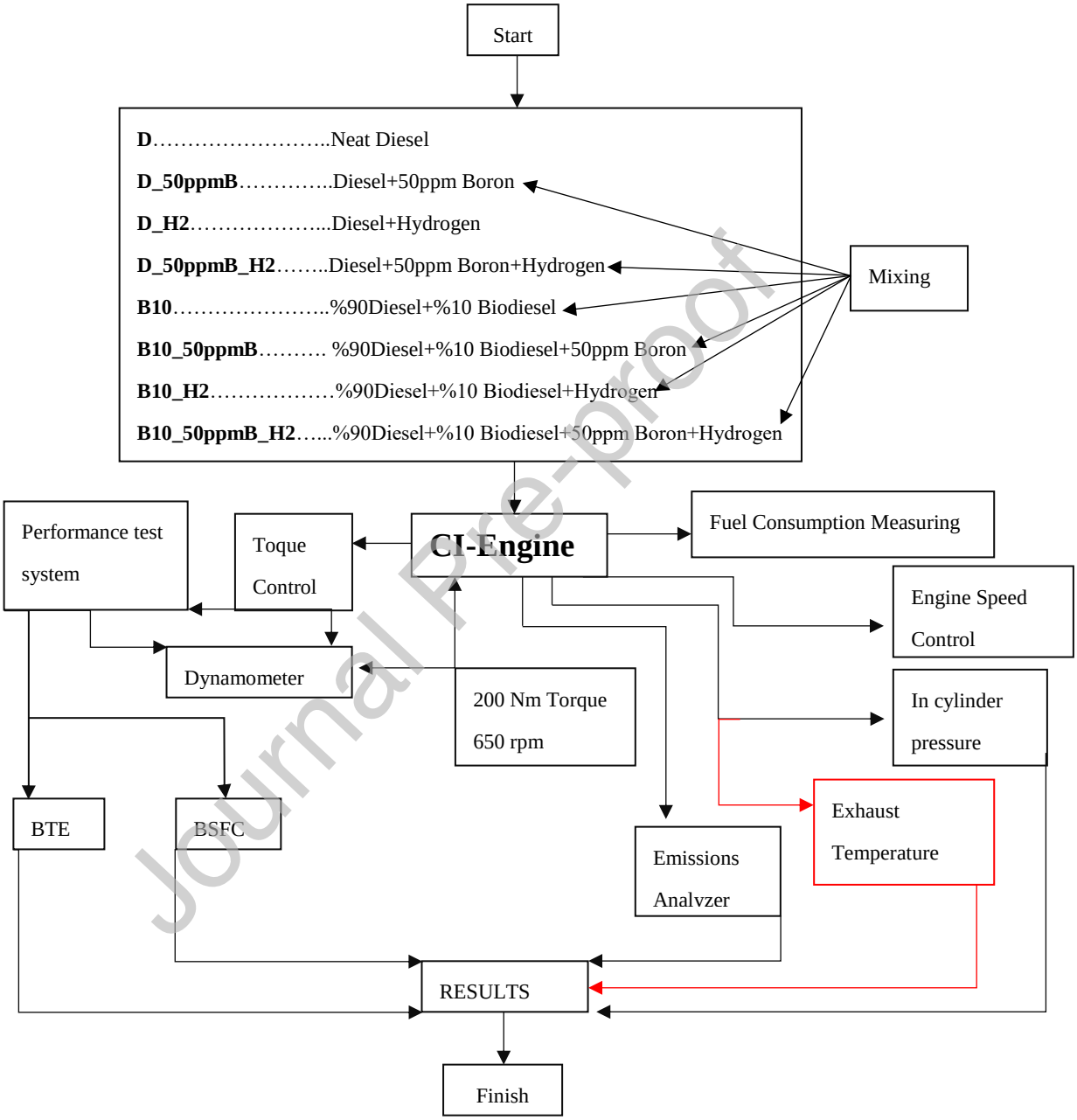

Fig. 1. Experimental Workflow

The test process is presented in Figure 1. According to this process, eight different fuel mixtures were tested in a compression ignition diesel engine at 650 rpm engine speed and 200 Nm engine load. PCS performance measurement system, eddy current dynamometer, diesel test engine, fuel consumption

measurement system, in-cylinder pressure measurement unit, exhaust analyzer, fuel mixing instrument, hydrogen cylinders and gas pressure reduction unit are the test equipment that will be discussed in detail in section 2.2. The codes given to the test fuels used in this study are shown in **Figure 1**. The liquid-liquid (diesel-biodiesel) fuel mixtures and liquid-solid (diesel/biodiesel-nanobor) fuel mixtures used in the experiments were mixed for 60 minutes at 800 rpm using a magnetic stirrer.

In order to obtain the basic test data of the diesel engine, the experiments were first started with pure diesel fuel. After the test of pure diesel fuel, the experiments were continued with the fuel mixture types D_H2, B10, B10_H2, D_50ppmB, D_50ppmB_H2, B10_50ppmB and B10_50ppmB_H2, respectively. The base values obtained from the pure diesel fuel test were compared with the test data of these fuel mixtures. In each test fuel change, the engine was operated for at least 15 minutes with the new fuel type. Data were started to be taken for the new fuel type after this 15-minute period. Thanks to this method, it was ensured that the data were not mixed up in fuel type changes and that healthy records were made. All experimental data were recorded. These recorded data were evaluated comparatively in the results section.

1.2. Experimental Setup and Equipment

In this study, a six-cylinder, heavy-duty, compression ignition engine was used as the test engine. Each cylinder of this test engine has a cylinder volume of 1945 cc. In the current study, diesel, biodiesel and hydrogen mixtures were used as fuel. In addition, nano boron was added to the liquid fuel as a nanoparticle. Liquid fuel consumption was measured with a precision balance. Liquid fuel consumption was recorded every 2 minutes. Hydrogen used as gaseous fuel is stored in storage cylinders at 200 bar pressure. Hydrogen, which is at 200 bar pressure, was reduced to 1 bar pressure in the pressure reduction station and transmitted to the intake manifold of the engine. The consumption of hydrogen gas was monitored with an ALICAT brand flow control unit. An eddy current dynamometer was used to measure engine torque and engine power. The engine speed was measured with an encoder with 1/360 degree sensitivity. A piezoelectric sensor was used to obtain the in-cylinder pressure. The experimental setup and equipment summarized above are visualized in **Figure 2**. The test equipment numbered in **Figure 2** is explained in detail in the following paragraph.

Instr.1 represents the test engine. This engine has a displaced volume of 11670 cc and a six-cylinder. Each cylinder has a bore of 133 mm and a stroke of 140 mm. The compression ratio is 16.5. Fuel is injected into cylinder 16 CA before the top dead center. The technical specifications of the test engine are shown in **Table 1**.

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Table 1

The Test Engine Properties

Bore and Stroke	133 mm, 140 mm
Number of cylinders	6
Displaced volume	11,670 cc
Compression ratio	16.5
Injection timing	16 'BTDC

Instr.2 is the intake manifold. The air intake to the engine is provided from the intake manifold. The hydrogen fuel used in the experiments is sucked into the cylinder with the intake air through a connection made to the intake manifold. **Instr.3** are hydrogen storage cylinders. Hydrogen can be stored in these storage cylinders at 200 bar pressure. **Instr.4** is a high-pressure-resistant, fiber-braided gas connection hose. This hose can withstand a maximum pressure of 350 bar. **Instr.5** represents the pressure reduction unit. **Instr.5.1** refers to the connection point and valve group of the other end of the high-pressure resistant gas hose connected to the hydrogen storage cylinders to the regulation unit. **Instr.5.2** is the regulator that performs the pressure reduction **(Table 2)**. Thanks to this regulator, the pressure of the high-pressure gas under 200 bar pressure can be reduced to the range of 1-10 bar. The inlet pressure of the regulator can be adjusted between 1-230 bar and the outlet pressure can be adjusted between 1-10 bar. The operating temperature of the regulator is between -20 and +70 degrees Celsius. The regulator throttles the gas to reduce the pressure of the 200 bar pressure gas to 1 bar pressure. As a result of the throttling of the gas, the gas expands on the other side of the regulator and its pressure decreases. There are also changes in the temperatures of the gases whose pressure decreases. The ratio of temperature changes to a pressure decrease in pressure reduction processes is called the Joule-Thomson coefficient [42].

Table 2

Gas regulator properties

Material	Yellow alloy of copper and zinc
Inlet and Outlet Ports	DN20
Inlet Pressure	0-230 bar
Outlet Pressure	0-10 bar
Diaphragm and Seals	Mebran
Operating Temperature Range	(-20 °C) - (+70 °C)
Dome Loading Port	M16x1,5
Layers	2
Inner Diameter	6,5 mm

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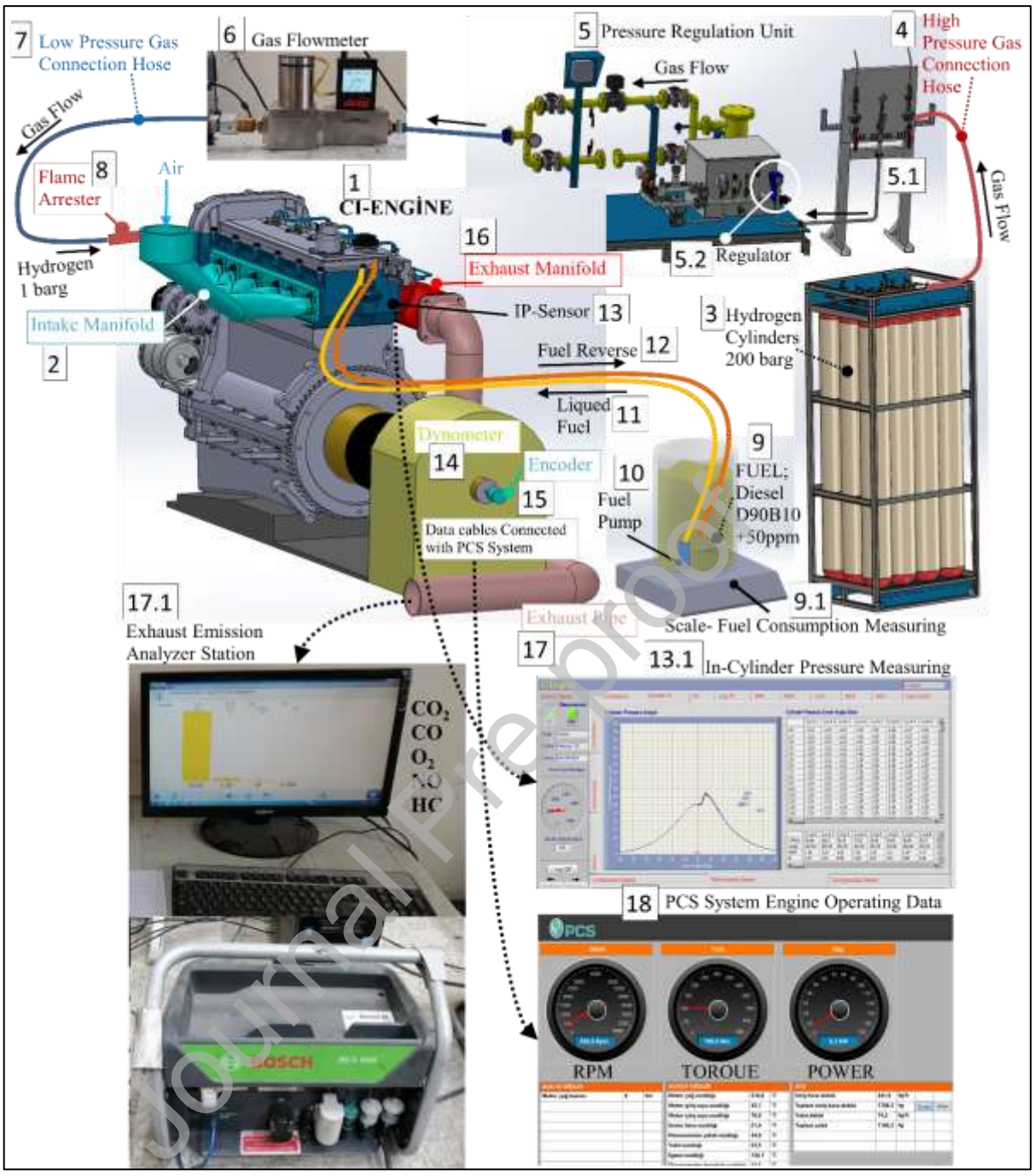

Fig. 2. Experimental Setup with instrument (Instr.) numbers

Unlike many gases, the temperature of hydrogen gas increases during pressure reduction at room temperature. This is because the inversion temperature of hydrogen (the inversion temperature of hydrogen is 202K) is below room temperature [43]. In other words, since hydrogen has a negative Joule-Thomson coefficient, its temperature increases during pressure reduction at room temperature [44]. Due to this feature of hydrogen, unlike other gases (such as methane which the inversion temperature of methane is 939 K), no heating process was required during pressure reduction in this study. **Instr.6** is an ALICAT MCR series flow controller. This flow meter increases the speed of the fluid by narrowing the cross-sectional area of the flow in the outlet region. According to the Bernoulli

principle, the pressure of the fluid decreases with increasing speed. The device measures the volumetric flow rate by detecting this pressure drop. The device can calculate the mass flow rate thanks to the fluid properties such as density defined in advance [45]. The maximum operating pressure of the ALICAT flow controller is 10 bar. Its technical specifications are presented in **Table 3**.

Table 3

ALICAT Flow Controller Technical Specifications

Accuracy	± (% 0,8 reading + % 0,2)
Repeatability	± % 0,2
Operating range	200:1
Maximum controllable flow rate	%102,4
Maximum measurable flow rate full scale	%128
Response time	100 ms (Adjustable)
Warm-up time	<1 second
Operating temperature	−10 ºC / +60 ºC
Humidity range (Non-condensing)	%0 - %100
Maximum internal pressure (Static)	145 psi
Test pressure	175 psi
Valve type	Normally closed
Ingress protection	IP40

Instr.7 is a low-pressure gas connection hose with a maximum pressure resistance of 10 bar. This connection hose performs the gas transfer between the pressure reduction unit, the flow controller and the engine intake manifold. **Instr.8** is a flame arrester. For safety, it is positioned at the end point of the gas line, i.e. the point where hydrogen enters the engine. **Instr.9** refers to the fuels used in the experiments. These fuels and the names given to the fuels are shown in **Table 4**.

Table 4

Fuel types and coding

Code	Explanation	Heat Values (Mj/kg)
D	Neat Diesel	42.70000
D_50ppmB	Diesel+50ppm Boron	42.70078
D_H2	Diesel+%18Hydrogen	48.44993
D_50ppmB_H2	Diesel+50ppm Boron+%18Hydrogen	48.48494
B10	%90Diesel+%10 Biodiesel	42.42600
B10_50ppmB	%90Diesel+%10 Biodiesel+50ppm Boron	42.42679
B10_H2	%90Diesel+%10 Biodiesel+%18Hydrogen	48.44034
B10_50ppmB_H2	%90Diesel+%10 Biodiesel+50ppm Boron+%18Hydrogen	48.53376

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The preparation of the experimental fuel mixtures is explained in detail in section 2.3. **Instr.9.1** is a DESIS-KF-H2W **(Table 5)** model precision scale used in fuel consumption measurement. The sensitivity is 0.5 grams. Fuel consumption was recorded in 2-minute periods in each experimental set. Fuel consumption amount was calculated using the mass difference between the start and end of consumption.

Tablo 5

DESIS-KF-H2W precision scale technical specifications

Technical Properties	
Weighing Capacity	15 kg
Weighing Accuracy	0.5 g
Minimum Weighing	10 g
Pan Size	336 x 223 mm
Resolution	0.5 gr.
Calibration	External calibration
Keypad	Membrane
Weighed Units	kg, g
Tare Ability	Yes
Reset Feature	Yes
Display	Backlit LCD display
Power Supply	220V AC

Instr.10 is a fuel pump that can provide fuel pressure up to a maximum of 5 bar. In this study, fuel pressure was set between 1.5-2 bar. **Instr.11** represents the fuel supply line. **Instr.12** is the fuel return line.

Table 6

PCB113B22 brand piezoelectric sensor properties

Measuring Range (for ±5V output)	34475 kPa
Useful Range (for ±10V output)	68950 kPa
Accuracy (±10%)	0,145 mV/kPa
Maximum Pressure	103425 kPa
Resolution	0,14 kPa
Resonance Frequency	≥500 kHz
Rise Time	≤1,0 μ second
Low Frequency Response (-5%)	0,001 Hz
Linearity	≤%1,0 FS

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Acceleration Sensitivity	≤0,0014 kPa/(m/s²)
Temperature Range (Operating)	-73, +135 °C
Maximum Flash Temperature	1649 °C
Sensing Geometry	Compression
Sensitive Element	Kuvars
Diaphragm	Invar (nickel-containing steel)
Sensor Material	Kuvars
Body Material	17-4 Stainless Steel

Instr.13 represents a piezoelectric sensor mounted on the cylinder head to measure in-cylinder pressure. When a force acts on SiO_2 (quartz) in the PCB113B22 **(Table 6)** brand piezoelectric sensor, Si^+ and O^- opposite charges change places. During this change, an electrical signal occurs in the sensor. Thanks to this signal, in-cylinder pressure is measured. [46-48]. **Instr.13.1** represents the program that processes the data coming from the in-cylinder pressure sensor. **Instr.14** is an eddy current dynamometer. It has a maximum torque of 600 Nm and a power of 150 kW. **Instr.15** is the encoder used to measure the engine speed. The number of pulses in one revolution is 360. **Instr.16** is the exhaust manifold.

Table 7

Bosch BAE 60 gas analyzer

Components	Measurement Range	Precision
CO	% 0,000 – 10,00	% 0,001
CO_2	% 0,00 – 18,00	% 0,01
HC	0 - 9999 ppm	1 ppm
O_2	% 0,00 – 22,00	% 0,01
NO	0 - 5000 ppm	1 ppm

Instr.17 is the exhaust pipe. The Bosch BEA60 exhaust analyzer (**Instr.17.1- Table 7)** is connected to the exhaust pipe to measure exhaust emissions. **Instr.18** represents the PCS engine test unit. Engine performance data were obtained with this unit.

1.3. Overview of Biodiesel and Biodiesel Production

Biodiesel is a biofuel produced by the chemical transformation of natural lipids. Natural oils such as vegetable oils, animal fats and used cooking oils are the raw materials of biodiesel [80]. Biodiesel is generally classified into four generations (**Figure 3**) in terms of the raw materials used. (1.) The first generation is biofuels produced from edible agricultural products. However, in this generation, edible products used for biodiesel production may compete with food products. Thus, the price of food

products may increase and create a problem of more difficult access to food for humanity. (2.) The second generation uses non-food biomass sources such as reed grasses, wood chips, and agricultural wastes for biodiesel production. Thus, the food hazard in the first generation is overcome, but biodiesel production from these food stocks is a more costly process. Studies and developments on this subject are still ongoing. (3.) The third generation uses algae for biodiesel production. Algae do not require arable land and can be grown quickly, so this production method is seen as a promising process. (4) The fourth generation is a new technology that involves advanced chemical transformations to convert biomass into fuel for biodiesel production. This technology is still in the very early stages of development [82].

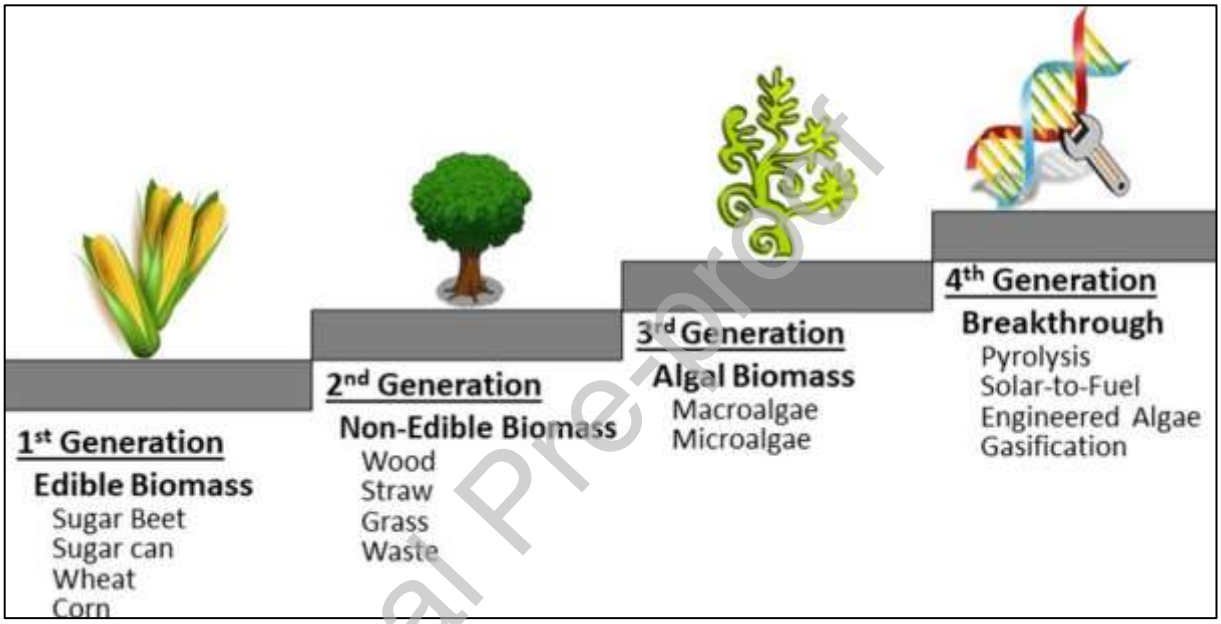

Fig. 3. Biofuel Generations [83]

The lipids found in vegetable oils, animal fats and recycled organic natural oils are generally composed of triglycerides. These triglycerides react with methanol in the presence of a catalyst. This process is called transesterification. Transesterifications used for biodiesel production are carried out in different methods depending on the catalyst and processes used. Alkaline-catalyzed transesterification process, acid-catalyzed transesterification process, enzyme-catalyzed transesterification process, ultrasonic irradiation, and Supercritical transesterification process can be given as examples of these methods [81]. **Figure 4** shows the process of converting feedstock to biodiesel. Organic oils react with methanol and a catalyst to form the transesterification process. As a result of this process, crude glycerin and crude biodiesel products are produced. Later, glycerin and biodiesel production is carried out by refining methods. The recovered methanol can be reused in the transesterification process. If recycled oil is to be used when producing biodiesel, esterification must be carried out using sulfuric acid and methanol before transesterification[80].

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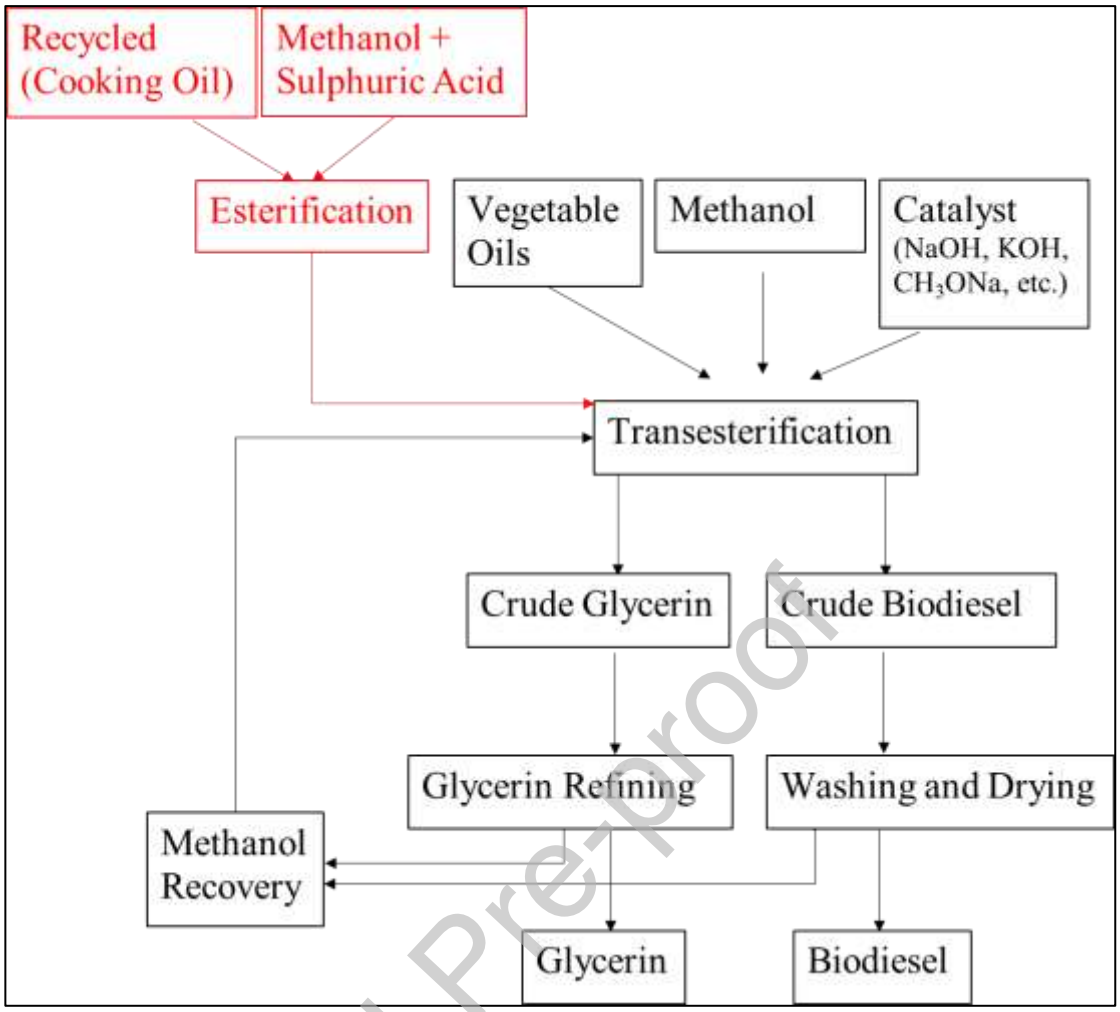

Fig. 4. Basic Scheme for Biodiesel Production.

1.4. Fuel Preparation

In this study, fuel mixtures consisting of standard diesel, biodiesel obtained from canola oil methyl ester, hydrogen and nano boron additive were used as experimental fuels. The properties of the fuels used are shown in **Table 9.** The biodiesel used in this study was supplied by a private company producing in the Marmara region of Turkey, which produces biodiesel from canola oil. The supplied canola oil-based biodiesel consists mostly of saturated fatty acids and its properties are presented in **Table 8**. These unsaturated fatty acids constitute approximately 93% of canola oil, including 61%-oleic acid ($C_{18}H_{34}O_2$), 21%-linoleic acid ($C_{18}H_{32}O_2$) and 11%-alpha-linoleic acid ($C_{18}H_{30}O_2$). The remaining 7% consists of saturated fatty acids such as Palmitic acid ($C_{16}H_{32}O_2$), Stearic acid ($C_{18}H_{36}O_2$) and others [51-53].

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Table 8

Properties of canola oil biodiesel [51]

Analysis	Unit	Method	Canola oil methyl ester
Ester content	%(m/m)	EN 14103	99.4
Density	g/cm^3	EN ISO 3675	0.883
Kinematic viscosity	mm^2/s	EN ISO 3104	4.60
Acid value	mgKOH/g	EN 14104	0.11
Iodine value	g iodine/100g	EN14111	118
Pour point	oC	ISO 3016	-12
Flash point	oC	ASTM D93	105
Heating value	MJ/kg	ASTM D240	39.96
Cold filter plug point	oC	EN 116	-15
Water content	mg/kg	ENISO12937	260
Stoichiometric ratio	Air/Fuel		13.8 [84]

Standard diesel was used as the base liquid fuel in this study. In the present study, the performance and emission values of other fuel mixtures were discussed by comparing them with standard diesel fuel. The liquid-liquid fuel mixture formed by 90% Standard diesel fuel and 10% biodiesel fuel constituted the other base liquid fuel of this study. The hydrogen mixed in the experiments conducted with the standard diesel and 10% biodiesel mixture was transmitted into the cylinder from the engine intake manifold in a way that would replace 18% of the liquid fuel consumption. The calorific values of the test fuels are presented in **Table 4.**

Table 9

Fuels Specifications

Specifications	Hydrogen [49]	Boron[41]	Diesel [41]
Chemical formula	H_2	B	$\sim C_{12}H_{23}$
Density (kg/m^3)	0,09 (gaseous)	3,580 (25 °C)	840, (20 °C)
Cetane number	-	-	>55.8
Stoichiometric ratio	34,48 Air/Fuel	-	14.5 Air/Fuel
Auto ignition Temperature	585 °C	-	186–230 °C
Low Heat Value (LHV) MJ/kg	120	58.28 [50]	42.7
Melting Point	-	2400 °C	-
Particle size	-	20 nm	-
Form / Color	Gas	Powder / Brown	Liquid
Specific Gravity	-	2.46	-
Molecular weight	-	10.81	-
Crystal structure	-	Hexagonal	-
Purity	99,999 %	99,9%	-

The nano boron additive used in liquid fuels is 50 ppm. 0.05 g of nano boron was added to every 1000 g of liquid fuel. The particle size of the nano boron used as an additive is 20 nanometers. As illustrated in **Figure 5**, the liquid-liquid and liquid-solid mixtures were mixed using a magnetic stirrer at 800 rpm for 60 minutes. The fuel mixtures coded in **Table 4** were thus prepared for the experiment. The prepared fuels were used in the experiment without waiting. Thus, a possible sedimentation was avoided. In addition, the samples taken from the mixtures were kept for 24 hours and no significant sedimentation was observed.

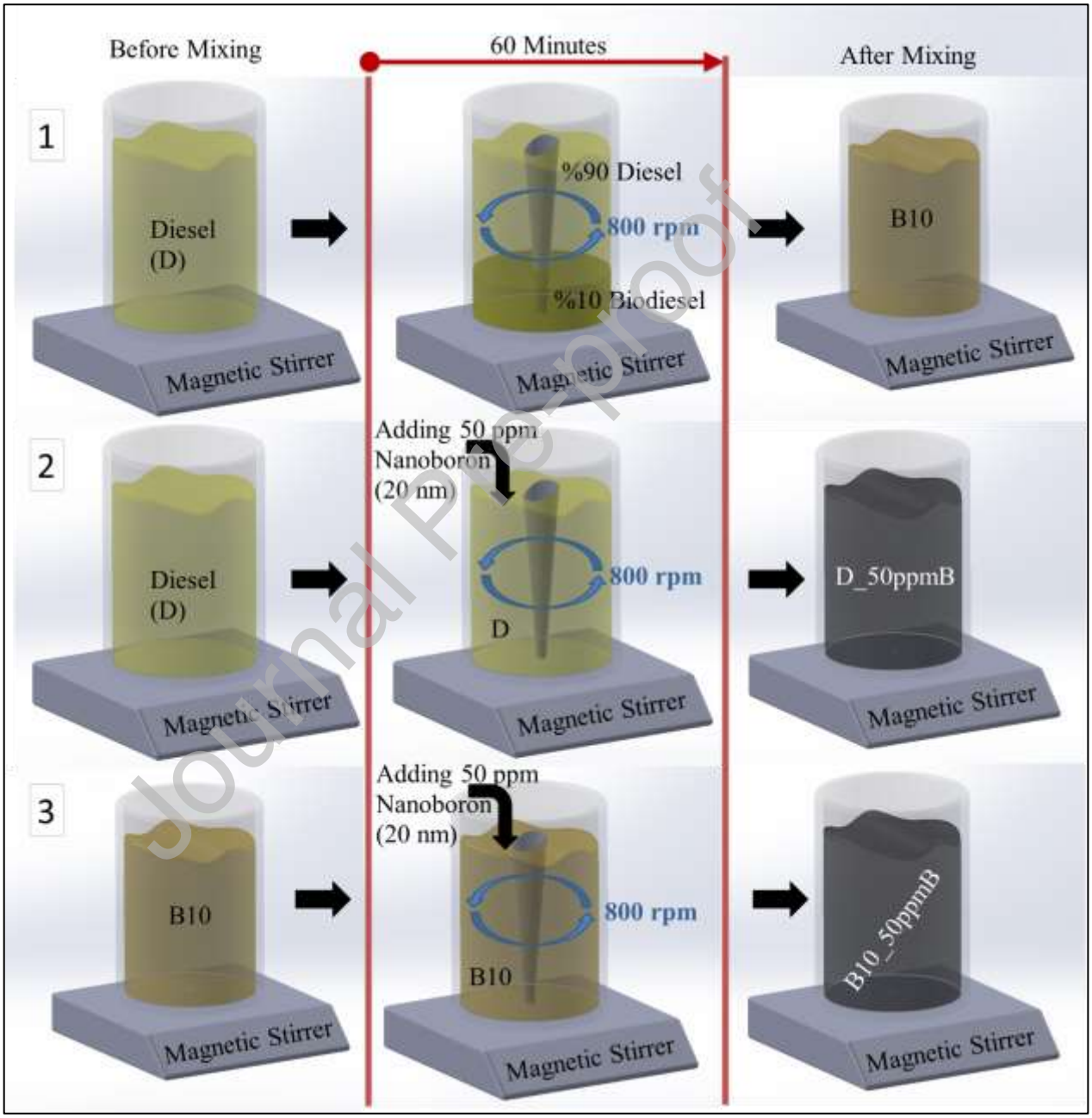

Fig. 5. Fuel Preparation Process

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1.5. Uncertainty analysis

In the current study, the uncertainty analysis was calculated using Equation 1. Results are presented in **Table 10**. Here, WR represents the uncertainty value, x1, x2, x3,..., xn denote the independent variables, and w1, w2, w3,..., wn represent the uncertainty values of each parameter [41, 54, 55].

Table 10

Uncertainty analysis

Item	Uncertainty ratio
NO_x	0.71%
CO	1.73%
HC	1.26%
CO_2	0.54%
Bte	1.68%
Bsfc	1.47%
Pressure Sensor	1.55%
Total Uncertainty	**3.57%**

$$\boldsymbol{W_R = \left[\left(\frac{\partial R}{\partial x_1} * w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} * w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} * w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} * w_n\right)^2\right]^{1/2}} \quad \textbf{[1]}$$

The total uncertainty analysis calculation was performed according to Equation 2. Here, TU represents the Total Uncertainty, and U denotes the uncertainty of each parameter.

$$\boldsymbol{TU = \sqrt{UNO^2 + UCO^2 + UHC^2 + UCO_2{}^2 + UBte^2 + UBsfc^2 + UPS^2}} \quad \textbf{[2]}$$

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2. DISCUSSION

2.1. Engine Performance

Brake thermal efficiency (BTE) and Brake-specific fuel consumption (BSFC) are important intercorrelated factors in evaluating engine performance. In this study, BTE and BSFC were calculated using equation 3 and equation 4. Where, Pb - brake power, ṁ - fuel flow rate, and LHV – calorific value.

$$\boldsymbol{BTE = \frac{P_b}{\dot{m} * LHV}} \quad \textbf{(\%)} \quad \textbf{[3]}$$

$$\boldsymbol{BSFC} = \frac{\dot{m}}{P_b}\ (\text{g/kWh}) \qquad \textbf{[4]}$$

The calorific values of the fuel mixtures were calculated with equation 5. Where LHV_K - calorific value of the mixed fuel, $m_{1,2...n}$ - fuel mass amount, $LHV_{1,2,...n}$ - calorific values of fuels.

$$\boldsymbol{LHV_K} = \frac{\boldsymbol{m_1 * LHV_1 + m_2 * LHV_2 + \cdots + m_n * LHV_n}}{\boldsymbol{m_1 + m_2 + \cdots + m_n}} \qquad \textbf{[5]}$$

Heat release rates are calculated according to Equation 6. Where dQn/dΘ: Net heat release rate, Ɣ: Heat capacity rate, P: In-cylinder pressure, V: In-cylinder volume, Θ: Crankshaft angle.

$$\frac{\mathbf{dQ_n}}{\mathbf{d}\Theta} = \frac{\gamma}{\gamma - 1} * P * \frac{dV}{d\Theta} + \frac{1}{\gamma - 1} * V * \frac{dP}{d\Theta} \qquad [6]$$

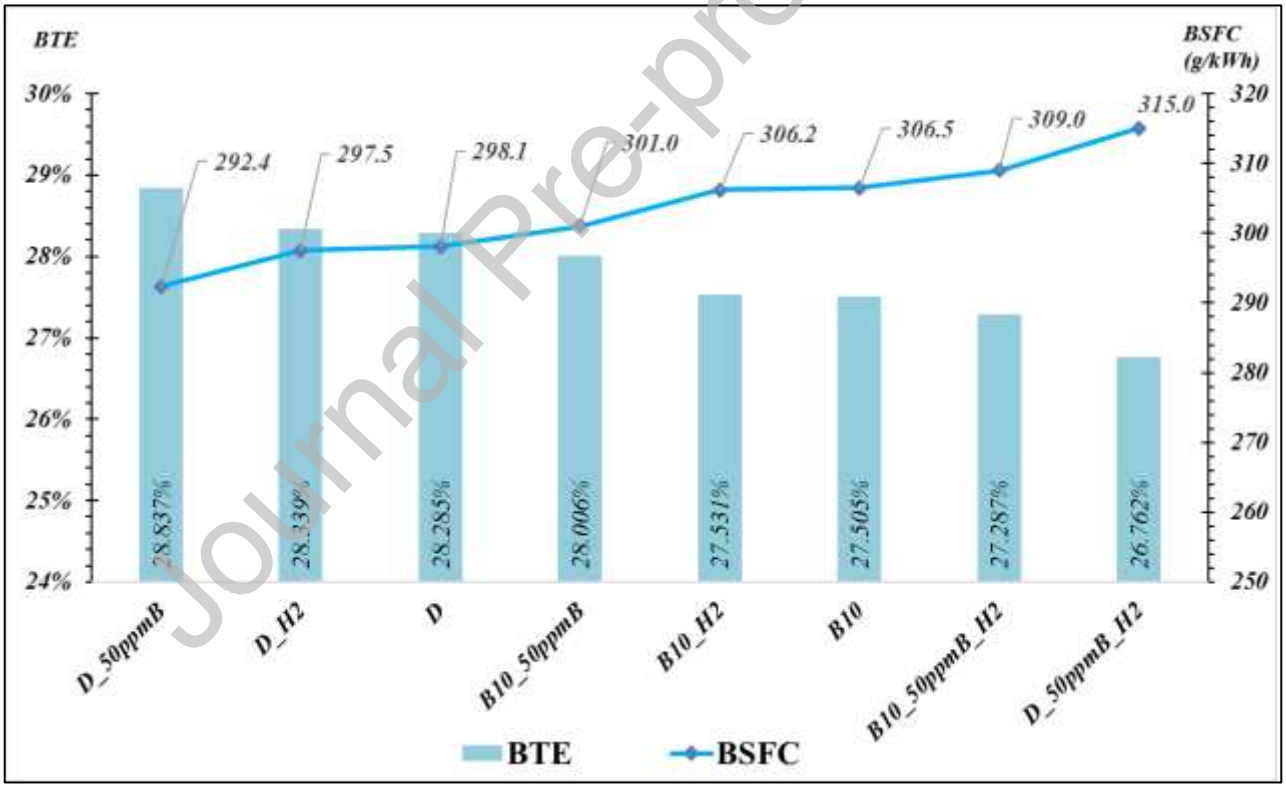

Fig. 6. Brake Thermal Efficiency and Brake Specific Fuel Consumption

The thermal efficiency (BTE) and specific fuel consumption (BSFC) data obtained in this study are presented in **Figure 6**. According to the results, the highest thermal efficiency was attained in the experiments conducted with D_50ppmB fuel. When the thermal efficiency values obtained in the experiments with standard diesel (D) fuel were compared with D_50ppmB and D_H2 fuels, an efficiency increase of 1.95% and 0.19% was obtained, respectively. In B10_50ppmB, B10_H2, B10,

B10_50ppmB_H2 and D_50ppmB_H2 fuels, an efficiency decrease of 0.99%, 2.66%, 2.75%, 3.53% and 5.38% was obtained, respectively.

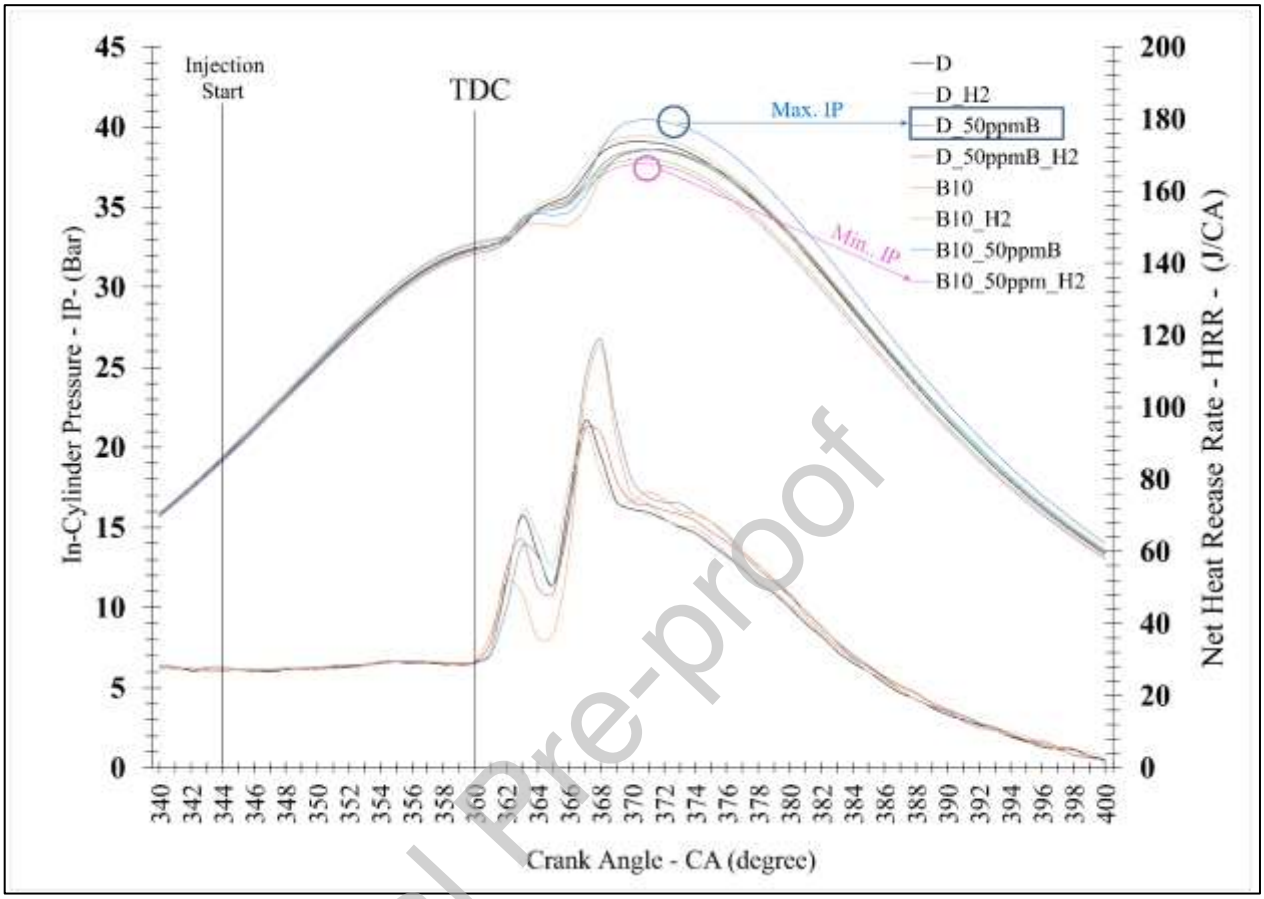

Fig. 7. In-Cylinder Pressure and Heat Release Rate

Figure 7 shows the in-cylinder pressure and net heat release rates obtained from the tests conducted with eight different test fuels. The 40.48 bar in-cylinder pressure obtained with D_50ppmB fuel is seen as the highest in-cylinder pressure value in this study. The maximum in-cylinder pressures of other fuel mixtures belong to the fuels D_H2, D, B10, D_50ppmB_H2, B10_50ppmB, B10_H2, B10_50ppmB_H from the highest to the lowest value (39.46, 39.09, 38.59, 38.58, 38.53, 38, 37.67 bar, respectively).

Thermal efficiency (BTE), specific fuel consumption (BSFC), in-cylinder pressure value and net heat release rates are discussed in more detail below in comparison.

2.1.1. Standard diesel (D) and diesel with 10% biodiesel additive (B10)

As seen in **Figure 6**, the BTE value of standard diesel is 28.285% and the BTE value of diesel fuel (B10) with 10% biodiesel additive is 27.505%. The thermal efficiency of standard diesel is 2.75% higher than B10 fuel. The reason for this is that the presence of biodiesel in standard diesel fuel

reduces the thermal efficiency of the fuel. The fuel with biodiesel additive has increased the mass flow of the fuel in order to produce the same power as standard diesel. This has increased the BSFC value. Accordingly, the thermal efficiency of biodiesel additive fuel has decreased [56]. In other words, since the thermal efficiency of B10 fuel is lower than that of standard diesel, it has to consume more fuel to produce the same power as standard diesel at the same engine speed and torque value [57-59]. As a result, the BSFC has increased and the BTE value has decreased.

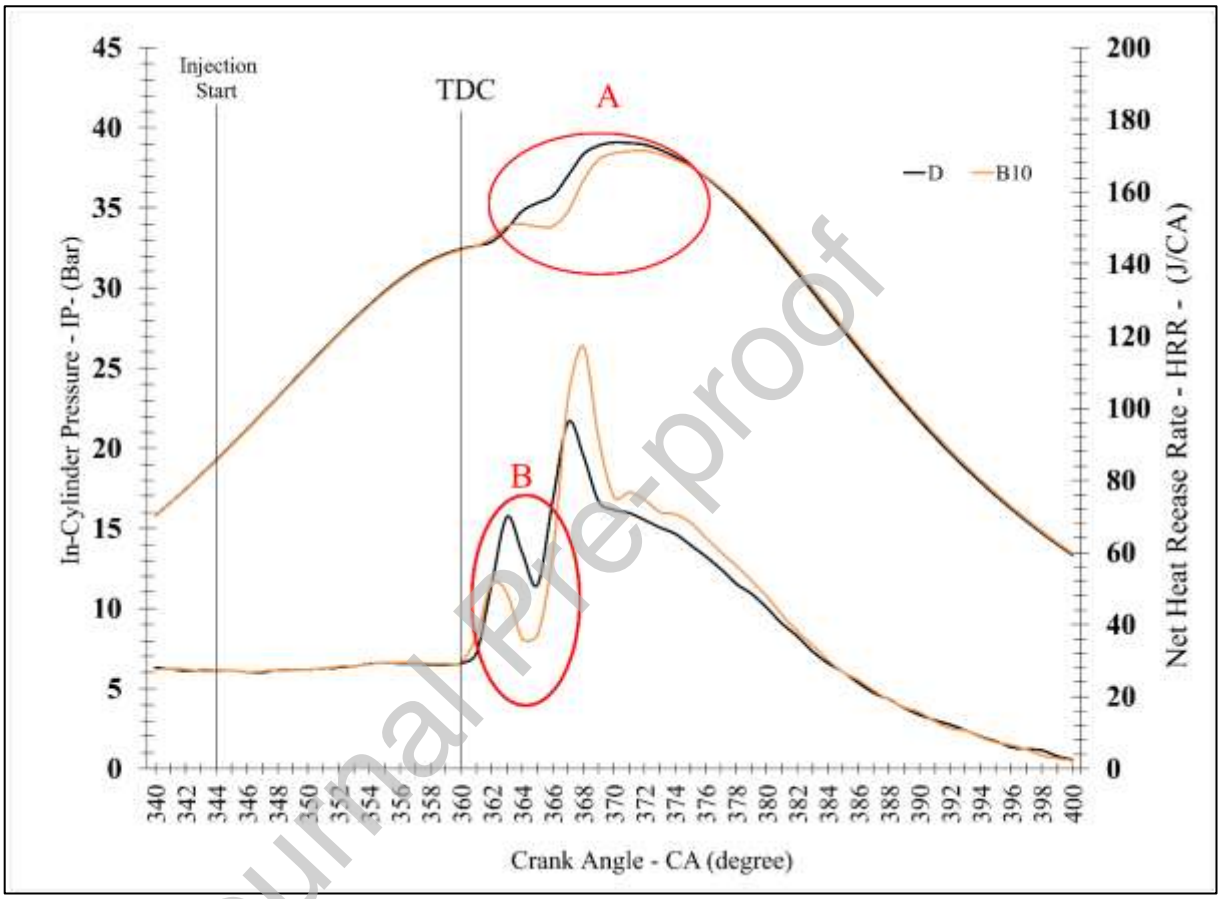

Fig. 8. In-Cylinder Pressure and Heat Release Rate of Fuel of **D and B10**

Figure 8 shows the in-cylinder pressure and heat release rates of D and B10 fuels. According to the graph, the combustion pressure of B10 fuel is lower than standard diesel fuel (See region A). This is because the viscosity of biodiesel is higher than standard diesel. While pure biodiesel has a viscosity of 4,290 mm2/s, standard diesel has a viscosity of 2,719 mm2/s. The presence of 10% biodiesel in diesel increased the viscosity of B10 fuel compared to standard diesel. This reduced the atomization ability of the fuel [57]. B10 fuel vaporized in the cylinder for a longer time than standard diesel fuel. In addition, B10 fuel took more heat from the cylinder for vaporization and therefore decreased the in-cylinder pressure (See region B). This was a factor in the decrease in thermal efficiency. The combustion event in B10 fuel occurred at more advanced crank angles than standard diesel fuel. The obtained results are parallel to [56, 57 and 59]. The ignition delay of B10 fuel is relatively shorter (less

than 1 degree CA) than standard diesel fuel. This is because the cetane number of Biodiesel fuel is higher than standard diesel fuel, it has higher oxygen content and lower stoichiometric air requirement [59-61].

2.1.2. The effect of nanoparticles

As a result of the experiments conducted in this study, it is seen that the nanoparticle (nanoboron) additive to D and B10 fuels has positive effects on thermal efficiency. D_50ppmB has 1.95% higher thermal efficiency than D (standard diesel). B10_50ppmB has 1.82% higher thermal efficiency than B10. According to these results, it can be clearly said that the nanoparticle additive improves the efficiency of D and B10 fuels. There are several reasons for this situation. The first of these is that boron has a high volumetric and gravimetric heating value. Another factor is that nanoparticles increase the surface area/volume ratio. Thanks to the increase in the surface area/volume ratio, flame spread increased and a more homogeneous combustion was allowed. This ensures that a greater portion of the fuel entering the cylinder participates in combustion. These factors had a positive effect on thermal efficiency [41, 62, 63]. In addition, nanoparticle additives improved heat transfer (nanoparticles can remain suspended in the air as embers for a certain period of time and transfer heat by radiation, thus improving heat transfer), chemical process formation and air-fuel mixture ratio, therefore ensuring more efficient combustion of the fuel in the combustion chamber [64].

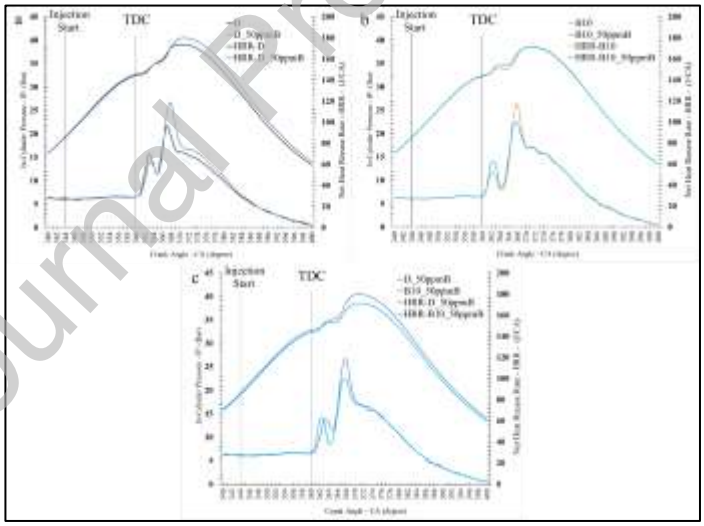

Fig. 9. Effect of nanoparticles on **D** and **B10** fuels

Figure 9-a graph shows the in-cylinder pressure (IP) and heat release rates (HRR) between D and D_50ppmB fuels. **Figure 9-b** is the IP and HRR graph between B10 and B10_50ppmB fuels. As seen in **Figure 9-a, b** graphs, nanoparticle (nano boron) addition to D and B10 fuels increased the combustion pressure. This had a positive effect on the thermal efficiency of both D and B10 fuels. As seen in **Figure 6**, the thermal efficiency of nano-boron-added fuels is higher than the thermal efficiency of the fuel to which it was added. **Figure 9-c** presents the comparison of D_50ppmB and B10_ppmB fuels. The combustion pressure of D_50ppmB is higher than B10_ppmB. At the same time, the thermal efficiency of D_50ppmB is higher than B10_ppmB (**Figure 6**). The presence of

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biodiesel in diesel fuel decreased the thermal efficiency. Because the calorific value of biodiesel is lower than standard diesel. Therefore, in order to produce the same power as standard diesel at the same engine speed and under the same load, it has consumed more fuel in terms of mass. In addition, since the viscosity of biodiesel is higher than standard diesel, the atomization feature of the fuel with biodiesel additive has deteriorated. Therefore, just as the thermal efficiency of D is higher than B10, it is logical that the thermal efficiency of D_50ppmB is higher than b10_50ppmB. Looking at the literature, researchers who studied nanoparticle and diesel blends [65-70, 76-79] reported similar results to this study regarding engine performance.

2.1.3. The effect of hydrogen

In this study, the in-cylinder pressure (IP) and heat release rates (HRR) obtained in the experiments carried out with hydrogen addition from the intake manifold are shown in **Figure 10**. **Figure 10-a** is the IP and HRR graphs of D and D_H2 fuels. **Figure 10-b** is the IP and HRR graphs of B10 and B10_H2 fuels. According to the BTE and BSFC graphs in **Figure 6**, it is seen that the BTE of D_H2 is relatively higher than D and the BTE of B10_H2 is relatively higher than B10. The thermal efficiency of D_H2 is 0.19% higher than D and the thermal efficiency of B10_H2 is 0.09% higher than B10. This situation can be attributed, firstly, to the high thermal efficiency of hydrogen fuel. As a result of the addition of hydrogen to the experiments carried out with standard diesel (D) and B10 fuels, some of these liquid fuels were replaced by hydrogen. After replacing some of the liquid fuels with hydrogen, the liquid fuel consumption decreased. Adding hydrogen resulted in positive effects on the specific fuel consumption due to the high calorific value of hydrogen. Another factor, as seen in **Figure 10**, combustion pressure increased relatively in the experiments conducted with the addition of hydrogen to both D and B10 fuels. This is also a value factor in which hydrogen affects thermal efficiency. The use of hydrogen together with B10 increased the combustion pressure, especially in the A region in **Figure 10-b**. It also increased the evaporation feature of the fuel in the B region in **Figure 10-b** and prevented it from drawing too much heat from the cylinder. In this case, it provided an increase in the combustion pressure in the A region and thus an increase in the thermal efficiency. In summary, the use of hydrogen together with D and B10 fuels resulted in an improvement in thermal efficiency and specific fuel consumption due to the high energy content, high flame speed, wide flammability limits and ignition properties of hydrogen, which encourage better combustion [6-8, 73]. The results found in this study are similar to [6-9]. On the other hand, the simultaneous addition of hydrogen and nanoparticles to D and B10 fuels caused a slight decrease in thermal efficiency. The injection start time of the test engine used in this study is 16 CA BTDC. It is thought that this injection start time does not create a suitable ignition delay interval for the combustion of hydrogen and nanoparticles together with liquid fuel. Because the high flame speed and fast ignition properties of hydrogen are combined with the combustion acceleration properties of nanoparticles, it is evaluated that the current injection start time is too early. Therefore, combustion is impaired. The BTE value of D_50ppmB_H2 and B10_50ppmB_H2 fuels was negatively affected for this reason. It is thought that advancing the

injection start time from 16 BTDC in the simultaneous use of hydrogen and nanoparticles will solve this problem.

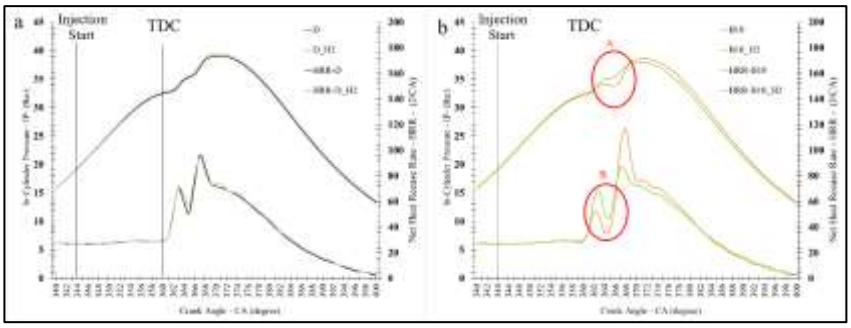

Fig. 10. Effect of hydrogen

2.2. Emissions

As seen in the CO graph (**Figure 11 - a**), the highest emission value belongs to B10 (diesel with 10% biodiesel added) fuel. The second highest CO emission is standard diesel fuel. Since biodiesel has a longer chain structure, it contains more carbon. Therefore, adding biodiesel to standard diesel (D) has increased the amount of carbon in the fuel and therefore CO emission has increased. Additionally, the increase in CO emissions can be attributed to the deterioration of combustion with biodiesel. Hydrogen addition has positive effects in terms of CO emission. It reduces the carbon content in the mixture and improves the combustion quality since it burns at high temperatures, thus reducing CO. The use of boron reduces CO emissions in pure diesel and biodiesel-diesel mixtures. However, when used with hydrogen-added fuel mixtures, CO emission increases. This means that the use of Hydrogen and Boron together has a negative effect on combustion formation. Because, it is thought that the injection start time does not create a suitable ignition delay interval for hydrogen and nanoparticles to burn together with liquid fuel. Since the high flame speed and rapid ignition properties of hydrogen are combined with the combustion acceleration properties of nanoparticles, it is evaluated that the current injection start time is too early. (The injection start time of the test engine used in this study is 16 CA BTDC.) Therefore, combustion is impaired and the amount of CO is increased. With the deterioration of combustion, the fuel that entered the cylinder could not participate in combustion and was thrown out of the exhaust when hydrogen and nano boron were used together. This situation resulted in an increase in HC emissions. In addition, since there was no complete combustion, the temperature in the cylinder would be relatively lower, and a decrease in NO emissions was observed.

When the CO_2 graph **(Figure 11 - b**) is considered, emission values show significant changes according to fuel mixtures. The emission amount, which is 931 g/kwh when pure diesel fuel is used, increases to 941 g/kwh with the addition of biodiesel. Biodiesel has a long chain structure and contains more carbon. Therefore, it creates more CO2 emissions. However, when hydrogen and boron were added to the mixtures separately, the addition of hydrogen provided a greater improvement in emissions compared to boron. HC emissions provide important information about the combustion

process. It indicates the amount of fuel that was not completely burned or partially burned during combustion. The separate use of hydrogen and nanoboron together with standard diesel (D) and B10 improved the HC emission value. On the other hand, the use of hydrogen and nanoboron together in D and B10 impaired combustion. This situation resulted in high HC emissions. The increase in HC emissions from the triple use of hydrogen and nanoboron with liquid fuel is related to the injection start time. The rapid flame spread of hydrogen and the effect of nanoparticles to accelerate combustion did not create a suitable condition for combustion at the current injection start time of the test engine. Here, it is seen in the graph (**Figure 11 - c**) that the triple mixture of Biodiesel, Hydrogen and nanoboron created the worst combustion.

The amount of NO emission varies depending on the high temperature in the combustion chamber [10, 11, 71-75]. High in-cylinder pressure results in higher in-cylinder temperature and at the correct crank angle value, these two factors create high efficiency. The highest in-cylinder pressure value achieved in the experiments in this study belongs to the D_50ppmB fuel. Therefore, it is logical that the highest NO emission belongs to the D_50ppm fuel, which is the fuel type with the highest thermal efficiency. The NO emission value is 3.74 g/kwh in the use of a diesel-nano boron (D_50ppm) mixture. The NO emission value of pure diesel fuel is 3.62 g/kWh. Thus, it is seen that the addition of nano boron to diesel increases NO emission by 3.15%. On the other hand, it is observed that the use of hydrogen has a positive effect on all fuel mixtures. The NO emission value, which is 3.62 g/kwh in the use of pure diesel, decreases by 32.6% to 2.44 g/kwh in the D-H2 mixture. In addition, the NO emission value, which is 3.60 g/kWh when B10 (90% diesel + 10% biodiesel) fuel is used, decreases by 29.72% to 2.53 g/kWh when B10_H2 fuel is used.

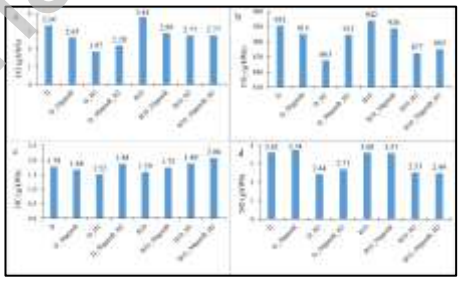

Fig. 11. Emissions

As a result of the experiments, the effects of nanoparticle addition to diesel and 10% biodiesel-added diesel fuels on emissions were discussed. According to results; It was observed that ppm nano boron addition to pure diesel fuel reduced CO, CO_2 and HC emission values by 20.66%, 1.82 and 5.62%, respectively. However, it increased NO emission by 3.21%. 50 ppm nanoboron addition to B10 fuel reduced CO and CO_2 emissions by 25.15% and 1.7%, respectively, while increasing HC emission by 9.14%. No significant change was observed in NO emission. As a result of the experiments, the effects of nanoparticle addition to diesel and 10% biodiesel-added diesel fuels on emissions were discussed. It

was observed that ppm nano boron addition to pure diesel fuel reduced CO, CO_2 and HC emission values by 20.66%, 1.82 and 5.62%, respectively. However, it increased NO emission by 3.21%. 50 ppm nanoboron addition to B10 fuel reduced CO and CO_2 emissions by 25.15% and 1.7%, respectively, while increasing HC emission by 9.14%. No significant change was observed in NO emission.

3. CONCLUSION

In this study, alternative fuel research was conducted in a compression ignition engine using standard diesel, biodiesel, nanoboron and hydrogen fuels. Nano boron additive increased the thermal efficiency of pure diesel and 10% biodiesel-added diesel (B10) fuels. It improved CO and CO_2 emissions. Using hydrogen together with diesel and B10 fuels improved the thermal efficiency. It reduced NO emissions. In addition to these important results, the results obtained from the current study are summarized below.

1- In the experiments carried out with standard diesel (D) fuel, when the thermal efficiency values obtained were compared with D_50ppmB and D_H2 fuels, an efficiency increase of 1.95% and 0.19% was achieved, respectively. On the other hand, when compared with B10_50ppmB, B10_H2, B10, B10_50ppmB_H2 and D_50ppmB_H2 fuels, an efficiency decrease of 0.99%, 2.66%, 2.75%, 3.53% and 5.38% was attained, respectively.

2- When the thermal efficiencies of standard diesel (D) and 10% biodiesel added diesel (B10) fuels were compared, it was seen that the efficiency of Standard diesel (D) was 2.75% higher than B10.

3- D_50ppmB (standard diesel + 50 ppm nano boron) fuel has the highest thermal efficiency (28.837%) among all fuel mixtures. Nanoparticle addition to standard diesel (D) and 10% biodiesel-added diesel (B10) fuels increased the thermal efficiency and combustion pressure of D and B10 fuels. D_50ppmB has 1.95% higher thermal efficiency than D, and B10_50ppmB has 1.82% higher thermal efficiency than B10.

4- 18% of the energy consumption of D and B10 fuels was replaced by hydrogen. Thermal efficiency was relatively increased in the experiments using hydrogen. It was observed that D_H2 produced 0.19% higher thermal efficiency than D, and B10_H2 produced 0.09% higher thermal efficiency than B10.

5- The injection start time of the test engine used in this study is 16 CA BTDC. It is thought that this injection start time does not create a suitable ignition delay interval for the combustion of

hydrogen and nanoparticles together with liquid fuel. Because the high flame speed and fast ignition properties of hydrogen are combined with the combustion acceleration properties of nanoparticles, it is evaluated that the current injection start time is too early. Therefore, combustion is impaired. The BTE value of D_50ppmB_H2 and B10_50ppmB_H2 fuels was negatively affected for this reason. It is thought that advancing the injection start time from 16 BTDC in the simultaneous use of hydrogen and nanoparticles will solve this problem.

6- As a result of the experiments, the effects of nanoparticle addition to diesel and 10% biodiesel-added diesel fuels on emissions were discussed. It was observed that ppm nano boron addition to pure diesel fuel reduced CO, CO2 and HC emission values by 20.66%, 1.82 and 5.62%, respectively. However, it increased NO emission by 3.21%. 50 ppm nanoboron addition to B10 fuel reduced CO and CO2 emissions by 25.15% and 1.7%, respectively, while increasing HC emission by 9.14%. No significant change was observed in NO emission.

7- The NO emission value is 3.74 g/kwh in the use of a diesel-nano boron (D_50ppm) mixture. The NO emission value of pure diesel fuel is 3.62 g/kWh. Thus, it is seen that the addition of nano boron to diesel increases NO emission by 3.15%. On the other hand, it is observed that the use of hydrogen has a positive effect on all fuel mixtures. The NO emission value, which is 3.62 g/kwh in the use of pure diesel, decreases by 32.6% to 2.44 g/kwh in the D-H2 mixture. In addition, the NO emission value, which is 3.60 g/kWh when B10 (90% diesel + 10% biodiesel) fuel is used, decreases by 29.72% to 2.53 g/kWh when B10_H2 fuel is used.

8- Hydrogen and Boron together has a negative effect on combustion formation. Because, it is thought that the injection start time does not create a suitable ignition delay interval for hydrogen and nanoparticles to burn together with liquid fuel. Since the high flame speed and rapid ignition properties of hydrogen are combined with the combustion acceleration properties of nanoparticles, it is evaluated that the current injection start time is too early. (The injection start time of the test engine used in this study is 16 CA BTDC.).Therefore, combustion is impaired and the amount of CO is increased. With the deterioration of combustion, the fuel that entered the cylinder could not participate in combustion and was thrown out of the exhaust when hydrogen and nano boron were used together. This situation resulted in an increase in HC emissions. In addition, since there was no complete combustion, the temperature in the cylinder would be relatively lower, and a decrease in NO emissions was observed.

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Conflict of Interest

The authors listed below have declared no conflicts of interest.