THERMODYNAMIC ANALYSIS AND EMISSION ASSESSMENT OF A DIESEL ENGINE FUELED WITH VARIOUS FUELS

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Master of Science Thesis

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I confirm that this thesis titled "THERMODYNAMIC ANALYSIS AND EMISSION ASSESSMENT OF A DIESEL ENGINE FUELED WITH VARIOUS FUELS" prepared by İbrahim YILDIZ is appropriate as a thesis for the degree of Master of Science.

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THESIS DECLARATION

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

İbrahim YILDIZ

FARKLI YAKITLARLA YÜKLENEN BİR DİZEL MOTORUN TERMODİNAMİK ANALİZİ VE EMİSYON DEĞERLENDİRMESİ

(Yüksek Lisans Tezi)

İbrahim YILDIZ

UŞAK ÜNİVERSİTESİ
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ÖZET

Bu çalışmada BDF100 biyodizel ve JIS#2 dizel yakıtları dizel motorunu egzoz arıtmalı ve arıtmasız sistemler için 1800 dev/dak'da çalıştırmak için kullanılmıştır. Egzoz arıtma sistemi olarak Dizel Oksidasyon Katalizörü (DOC) ve Dizel Partikül Filtresi (DPF) ele alınmıştır. DPF malzemeleri olarak silikon karbür (SiC) ve kordierit kullanılmıştır. Yakıtlar egzoz arıtmalı sistem için 100 Nm ve 200 Nm motor yüklerinde test edilirken, egzoz arıtmasız sistem için 100 Nm, 200 Nm ve tam yükte (294 Nm) kullanılmıştır. Sisteme enerji, ekserji, çevresel, çevre-ekonomik, sürdürülebilirlik, termo-ekonomik ve eksergo-ekonomik analizler uygulanmıştır ve motorun egzoz emisyonları, partikül konsantrasyonu, kurum konsantrasyonu ve özgül yakıt tüketimi deneysel olarak değerlendirilmiştir. Biyodizel yakıtı temel olarak kızartma yağından elde edilen %100 biyodizeldir (BDF100). Yakıtlar, 4 silindirli, 3L, turboşarjlı ve ara soğutuculu dizel motorunu çalıştırmak için kullanılmıştır.

Tarama Hareketi Parçacık Boyutlayıcı (SMPS), motor egzoz emisyon partiküllerinin boyut dağılımını ölçmek için kullanılmıştır. THC (Toplam Hidro Karbon), NO_x, CO ve CO_2 egzoz emisyonları, parçacık sayıları (PN), kurum ve özgül yakıt tüketiminin ölçümü deney sırasında gerçekleştirilmiştir.

Bu tezden bulunanlar: (i) Egzoz emisyon değerlerinin çoğu (NO_x hariç) motor yükü ile ters orantılıdır. Bununla birlikte, motor yükü artarsa, NO_x emisyon değerleri de artmaktadır. (ii) Dizel yakıtının CO ve HC emisyon değerleri biyodizel yakıtından daha fazlayken, biyodizel yakıtının CO_2 ve NO_x emisyon değerleri genellikle dizel yakıtından daha yüksektir. (iii) Dizel yakıtının alt ısıl değeri (LHV), biyodizel yakıtının alt ısıl değerinden daha fazladır. (iv) Biyodizel yakıtının özgül yakıt tüketimi dizel yakıtına göre daha fazladır. (v) Dizel yakıtının partikül konsantrasyonu biyodizel yakıtından daha yüksektir. Ayrıca, maksimum toplam partikül konsantrasyonları her iki yakıt türü için de 100 Nm torkta hesaplanmıştır ve yakıtların partikül konsantrasyonları motor yükü ile ters orantılıdır. (vi) Kurum konsantrasyonu, motor yükü ile ters orantılıdır. Ayrıca, biyodizel yakıtının kurum konsantrasyonu, dizel yakıtından daha azdır. (vii) Biyodizel yakıtı minimum enerji verimine sahipken, maksimum enerji verimi dizel yakıtı için hesaplanmıştır. (viii) Enerji verimi motor yükü ile doğru orantılıdır. (ix) Tüm motor yüklerinde biyodizel yakıtı, dizel yakıtından daha yüksek ekserji verimine sahiptir. (x) Çevresel ve çevresel-ekonomik parametreler motor yükleri ile doğru orantılıdır. (xi) DOC, kordierit dizel partikül filtresi ile birlikte kullanıldığında, egzoz emisyonu partikülü azalma değeri %98.57 olarak bulunmuştur. Eğer DOC, SiC dizel partikül filtresi ile kullanılırsa, egzoz emisyon partikülünün %99.97'si önlenebilmektedir. Küçük bir fark olmasına rağmen, SiC dizel partikül filtresi kordieritten daha fazla egzoz emisyon partikülü önlemektedir. (xii) Biyodizel yakıtı, her motor yükü ve tüm arıtma sistemleri için (egzoz artıma sistemi dahil veya hariç) dizel yakıtından daha az entropi üretimine sebep olmaktadır. Biyodizel yakıt verim çevre ve ekonomik açılardan dizel yakıttan daha etkilidir. Ayrıca, biyodizel yakıtı dizel yakıtına göre her motor yükü ve egzoz arıtma seçeneğinde (egzoz arıtma dahil ve hariç) daha düşük toplam partikül sayısına ve entropi üretimine sahiptir.

Bilim Kodu **:** 625.04.01
Anahtar Kelimeler **:** Biyodizel, dizel, ekserji, emisyon, enerji, motor, nano-partikül, partikül madde, SMPS, termodinamik analiz, verim
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(M.Sc. Thesis)

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ABSTRACT

In this study, JIS#2 diesel and BDF100 biodiesel fuels are used to operate the diesel engine at 1800 rpm for with and without after treatment systems. After treatment systems are considered as Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF). The silicon carbide (SiC) and cordierite are used as DPF materials. The fuels are used in the diesel engine at 100 Nm, 200 Nm and full load (294 Nm) for without after treatment system test, while they are tested at 100 Nm and 200 Nm engine loads for after treatment systems. The exhaust emissions, particle concentration, soot concentration and specific fuel consumptions of the engine are experimentally evaluated, and the energy, exergy, environmental, enviroeconomic, sustainability, thermoeconomic and exergoeconomic analyses are performed. The biodiesel fuel is 100% biodiesel (BDF100) which is basically obtained from the cooking oil. The fuels are used to operate 4-cylinder, 3L, turbocharged and intercooled diesel engine.

Scanning Mobility Particle Sizer (SMPS) is used to measure the size distribution of the engine exhaust emission particles. The measurement of the THC (Total Hydro Carbon), NO_x, CO and CO_2 exhaust emissions, particle numbers (PN), soot, specific fuel consumptions are conducted during the experiment.

It is found from this thesis that (i) Most of the exhaust emissions rates (except NO_x) are inversely proportional to engine load. If the engine load increases, the NO_x emissions increase too. (ii) The CO_2 and NO_x emission rates of the biodiesel fuel are generally more than the diesel fuel, while the CO and HC emission rates of the diesel fuel are more than the biodiesel fuel. (iii) The lower heating value (LHV) of the diesel fuel is more than the LHV of the biodiesel fuel. (iv) The specific fuel consumption of the biodiesel fuel is higher than the diesel fuel. (v) The particle concentration of the diesel fuel is higher than the biodiesel fuel. Moreover, the maximum total particle concentrations are calculated at 100 Nm torque for both of the fuel types and the particle concentrations of the fuels are inversely proportional to the engine load. (vi) The soot concentration is inversely proportional to the engine load. Also, the soot concentration of the biodiesel fuel is less than diesel fuel. (vii) The maximum energy efficiency is found for the diesel fuel, while the biodiesel fuel has the minimum rate. (viii) The energy efficiency is directly proportional to the engine load. (ix) The biodiesel fuel has higher exergy efficiency than the diesel fuel at every engine load. (x) The environmental and enviroeconomic parameters are directly proportional to the engine load. (xi) When the DOC is used with cordierite diesel particulate filter, the exhaust emission particle reduction rate is found as 98.57%. If the DOC is used with SiC diesel particulate filter, 99.97% of the exhaust emission particle can be prevented. Despite the fact that there is a little difference, the SiC diesel particulate filter prevents more exhaust emission particle than cordierite. (xii) The biodiesel fuel causes less entropy generation than the diesel fuel for every engine loads and after treatment option (with and without after treatment). The biodiesel fuel is more effective than the diesel fuel in terms of efficiency, environmental and economic aspects. The biodiesel fuel has also less total nanoparticle concentration and entropy generation than the diesel fuel for every engine load and after treatment option (with and without after treatment).

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Keywords : Biodiesel, diesel, engine, energy, efficiency, emission, exergy, nano-particle, particulate matter, SMPS, thermodynamic analysis

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İbrahim YILDIZ

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NOMENCLATURE

Some of the symbols and abbreviations used in this study are presented below along with explanations.

Symbols	Explanation
a_i	*i*th deviation (-)
C	Mass ratios of Carbon of fuel (%)
C_{CO_2}	Enviroeconomic parameter ($/day)
c_{CO_2}	CO_2 emission price per kg-CO_2 ($/kg-$CO_2$)
c_p	Specific heat capacity (kJ/kgK)
$c_{p,air,in}$	Specific heat capacity of intake air (kJ/kgK)
$\dot{E}n_{air}$	Energy rate of air (kW)
$\dot{E}n_{exh}$	Exhaust energy rate of the system (kW)
$\dot{E}n_{fuel}$	Energy rate of fuel (kW)
$\dot{E}n_{loss}$	Energy loss rate of the system (kW)
$\dot{E}n_W$	Work rate of the system (kW)
$\dot{E}x_{air}$	Exergy rate of air (kW)
$\dot{E}x_{dest}$	Exergy destruction rate of the system (kW)
$\dot{E}x_{exh}$	Exhaust exergy rate of the system (kW)
$\dot{E}x_{fuel}$	Exergy rate of fuel (kW)
$\dot{E}x_{loss}$	Exergy loss rate of the system (kW)
$ex_{ch,i}$	Specific chemical exergy rates of the *i*th exhaust gas component (kJ/kmol)
$ex_{tm,i}$	Specific thermomechanical (physical) exergy rates of the *i*th exhaust gas component (kJ/kg)
$\dot{E}x_W$	Exergetic work rate of the system (kW)
H	Mass ratios of Hydrogen of fuel
h	Enthalpy (kJ/kg)

h_{air}	Enthalpy of the air (kJ/kg)
h_i	Enthalpy of the *i*th exhaust gas component (kJ/kg)
H_u	Lower Heating Value (LHV) of fuel (kJ/kg)
$H_{u,density}$	Lower heating values of the fuel (kJ/kg)
$H_{u,viscosity}$	Lower heating values of the fuel (kJ/kg)
k	Total number of experimental tests
K	Capital cost of the system ($)
$\dot{m}_{air}$	Mass flow rate of air (kg/s)
$\dot{m}_{fuel}$	Mass flow rate of fuel (kg/s)
$\dot{m}_i$	Mass flow rate (kg/s)
n	Speed of the engine (rpm)
O	Mass ratios of Oxygen of fuel (%)
$\overline{R}$	Universal gas constant (kJ/kmolK)
R_{en}	Thermoeconomic parameter (kW/$)
$R_{ex,loss}$	Exergoeconomic parameter for loss (kW/$)
$R_{ex,dest}$	Exergoeconomic parameter for destruction (kW/$)
S	Entropy (kW/K)
S_{gen}	Entropy generation rate (kW/K)
SI	Sustainability index (-)
$T_{air,in}$	Inlet temperature of the intake air (°C)
T_{cw}	Cooling water temperature of the engine (°C)
$t_{working}$	Working hours of the engine in a day (h/day)
T_0	Dead state (reference) temperature (°C)
$\dot{V}_{air}$	Volumetric flow rate of air (L/s)
x_{CO_2}	CO_2 emission releasing in a day (kg-CO_2/day)
y_{CO_2}	CO_2 emission value of the fuel (kg-CO_2/kWh)

$y_{env,i}$	Molar fraction of *i*th exhaust gas component in the environment (%)
y_i	Molar fraction of *i*th exhaust gas component in the exhaust gases (%)
$\bar{x}$	Average value of experiment tests (-)
x_g	Real value of the measurement/test result (-)
x_i	*i*th experimental measurement
α	Mass ratios of Sulphur of fuel (%)
ε_{fuel}	Chemical exergy factor of fuel
η	Energy efficiency of the system (%)
μ_{fuel}	Viscosity of fuel (mm^2/s)
ρ_{air}	Density of air (kg/m^3)
ρ_{fuel}	Density of fuel (kg/m^3)
σ	Standard deviation (-)
T	Torque of the engine (Nm)
ω	Angular velocity (rad/s)
ψ	Exergy efficiency (%)
$\sum \dot{E}n_{in}$	Total energy input rate of the system (kW)
$\sum \dot{E}n_{out}$	Total energy output rate of the system (kW)
$\sum \dot{E}x_{in}$	Total exergy input rate of the system (kW)
$\sum \dot{E}x_{out}$	Total exergy output rate of the system (kW)

Abbreviations	**Explanation**
BDF100	100% Biodiesel fuel
CPC	Condensate particle counter
CRS	Common rail system
DMA	Differential mobility analyzer
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DSPM	Dilution system for particle measurement

EGR	Exhaust gas recirculation
FSN	Filter smoke number
JIS#2	Japanese industrial standard diesel no:2
LPG	Liquid petroleum gas
LHV	Lower heating value
PM	Particulate matter
SiC	Silicon carbide
SOF	Soluble organic fraction
SMPS	Scanning mobility particle sizer
THC	Total hydro carbon

1. INTRODUCTION

Development of engines started with fire arms, especially the invention of the gun. Many serious studies have been carried out on the use of gunpowder as fuel towards the end of the 1600's. Initially, the piston (bullet) rises with the burning of the gunpowder in a horizontal cylinder (barrel) and then the idea that this piston can be taken back by the effect of the gravity force and the atmospheric pressure. In 1678, Abbe Jean de Hautefeuille described the idea of making a piston-cylinder device for the first time. It was proposed to pump water with the vacuum force that resulted in the cooling of the remaining air (gas) after the pressurized gases formed by burning the gunpowder in a combustion chamber are thrown out of the chamber. In fact, the power of vacuum was already explained by scientists, Evangelista Toricelli, Blaise Pascal and Otto von Guerricke [1].

The first internal combustion machine was built by Robert Street in 1794. This machine, which consists of a rotating cylinder and a moving piston, (cylinder head) was heated by means of a stove while the upper parts were cooled with water. In this first machine, a few drops of turpentine essence were used as a burning agent and the piston was moved upwards by a lever in order to be able to draw air cylinder to provide combustion. In addition, the piston could be moved upwards by burning the mixture (an external flame brought into contact with a gap in the cylinder head). The cylinders were cooled with a water jacket to create a lower pressure and allow the piston to turn down [1].

In 1824, the basic principles of internal combustion diesel engines were put out by Sadi Carnot. In these principles;

- Self-ignition of fuel in compressed air: According to this principle, air compressed to 15/1, heated to 300 ºC, is considered to burn dry wood parts.
- Compressing air before burning: Accordingly, it is contemplated that the burn is at a pressure greater than the atmospheric pressure, and the fuel is added at the end of compression. Thus the injector was discovered.
- Cooling of the cylinders: It has been thought that the cylinder walls must be cooled for a continuous operation.
- Using the heat of the exhaust gases, which is the result of combustion: Exhaust gases are passed through the pipes of a boiler. Nowadays, by utilizing this

principle, the utilization of residual heat of exhaust gases is being used in ships and in the industry [2].

In the following years, researchers as Samuel Brown, Samuel Morey, Lemuel W. Wright, William Barnett, Stuart Perry and Alfred Drake made important contributions to the development of the internal combustion engines with various designs. But, in the real sense of the birth of the internal combustion piston engine, Eugenio Barsanti and Felice Matteucci were invented the first version of the engine in 1853 [3].

Lenoir made his first commercial internal combustion machine in 1860. This machine was similar to the piston steamer and worked in principle with two stroke cycles. Unlike the steam engine, the air-fuel mixture entered the cylinder by piston and this mixture was ignited by a spark plug and pushed to the end of the piston stroke; while exhaust gases were thrown out on the return stroke [2]. Although Lenoir's machine works well, it is seen as a negative condition that the thermal efficiency is around 4% - 5% due to the presence of the atmospheric pressure.

Beau De Rochas proposed the following ideas to improve the efficiency of internal combustion engines in 1862:

- Faster expansion process
- Maximum possible cylinder volume and minimum cooling surface
- Minimum possible pressure at the start of expansion

Otto collaborated with Langen to manufacture a very large free piston machine. In 1876, Otto built a four-stroke machine, whose principle was set forth by Beau De Rochas. This machine is today's one-of-a-kind petrol/diesel engine. Due to the long expansion stroke, this engine, which had had 2 m height and 0.7 kW-2.2 kW power, allowed economical use of the energy [2].

It was patented by Herbert Akroyd Stuart, that an explosive mixture, flammable vapors or a mixture of air and gas would require a continuous spark or a heated ignition head to prevent premature burning and a permanent igniter with a cylinder and a seam in 1890.

In 1892, the first machine that gave the result that the temperature generated as a result of the compression of the air at a certain rate was higher than the combustion temperature of the fuel, was patented by Rudolf Diesel.

In 1893, Frank Duryea manufactured a machine with four stroke cycles which was initially uncooled and connected to a transmission system [2]. After compressing the air, the fuel started to be sprayed on the upper dead spot deliberately and started to burn without a pressure rise. As soon as the fuel was sprayed, the gas mass started to expand.

Due to the lack of fuel in Germany, Rudolf Diesel tried to develop the first machine to burn coal as fuel. But the fact that the cylinders were not cooled and the air was compressed to 100 kg/cm^2 caused the first machine of Rudolf Diesel to fail [2]. But the machine, which was made by Diesel in 1985, was successful. This machine was a machine with four strokes, compression end pressure ranging from 30 kg/cm^2 to 40 kg/cm^2, water-cooled and spraying the fuel with high pressure air.

The diesel engine, originally engineered by Rudolf Diesel, is a kind of internal combustion engine in which the chemical energy of the fuel is converted directly into mechanical energy within the engine cylinders on 1893. These engines produce up to 35,000 HP of power and are today the most power-producing machines [3-4].

The systems that convert fuel energy to motion energy and are obtained by burning fuel are called engines. The classification of the engines is generally made according to the fuel burning location, the cylinder numbers and cylinder combination forms. Engines are divided into two types depending on where the fuel is to be burned; external combustion engines and internal combustion engines. According to the cylinder numbers, they are separated as 2 cylinders, 4 cylinders, etc. On the other hand, sequence type, V type and X type are the types according to cylinder combination forms.

In external combustion machines such as steam turbines, steam is used to push the piston after it is produced outside the piston. In these types of engines, a boiler is needed to produce steam. The water is evaporated in these boilers. Steam is sent to the cylinder by pressure, pushing the piston down.

Internal combustion machines include diesel engines, gasoline engines and gas turbines. In diesel engines, fresh air is sucked into the machine cylinders or filled up strongly. Pressurized air (28-35 bar) and temperature (450-650 °C) are obtained in the cylinder by the piston. Fuel particles, sprayed into this hot air, are self-igniting as the temperature of the air is higher than the ignition temperature of the fuel. The main disadvantage of diesel engines is that the power available from a single unit is limited. Where high power is required, either multiple motors must be used or steam turbines must be considered.

In gasoline engines, the air-fuel mixture, mixed at certain ratios, is sucked into the cylinder or filled up strongly. The air-fuel mixture can be prepared by a so-called carburettor, as well as systems for injecting fuel or spraying fuel into the cylinder. The air-fuel mixture is compressed by the piston. As a result of compression, fuel forms a very flammable mixture with air. This mixture is not self-igniting as it is in diesel engines. A spark, formed between the electrodes of an electrical device (called as spark plug), ignites the air-fuel mixture. Since all of the fuel burns in the form of an explosion, these machines are also called "explosive engines". The high temperature gases generated in the combustion resulted in heat, which enables the crankshaft to rotate by means of a similar equipment to the diesel engines.

In gas turbines, compressed air is compressed from the compressor atmosphere. The pressure and temperature rise are sent to the combustion chamber. The temperature of the air sent to the combustion chamber is the value that will allow the fuel to be sprayed to burn. Thus, the pressurized and hot gases obtained are expanded in a turbine-like turbine structure, and as a result "work" is achieved [4].

Diesel engines can be produced with two or four-stroke. Four-stroke diesel engines are usually used in locomotives, ships and generator drives, requiring small, medium and large power loads. Diesel engines differ even if they are structurally similar to four-stroke gasoline engines because they have injection pumps and injection injectors instead of carburettors and spark plugs. Diesel engines can be used in power generating, power plants, locomotives, trucks, buses, cars, etc. The injection pump injects fuel into the cylinder through the injector hole with high pressure, moving through the gear and crankshaft. To facilitate ignition, spark plug can be used [5].

Motor vehicles have an important role in air pollution. This has made it necessary to develop emission control technologies. Diesel engines have become leaders in the heavy duty vehicle market because of their high efficiency, low operating costs, high durability and reliability. In recent years, the diesel engines are increasingly playing a role in the light utility vehicle market, especially due to the high fuel prices. This growth trend in the diesel engine market requires careful consideration of environmental impacts [6].

In diesel engines, particulate matter (PM), nitrogen oxides (NO), hydrocarbons (HC) and carbon monoxide (CO) are the most important pollutants in the exhaust gas that are formed as combustion products. Because, diesel engines work with lean mixture, and produce less CO and unburned HC than gasoline engines. However, PM and NO emissions are high in diesel engines [7-8]. When such situations are considered, the use of biodiesel fuels in diesel engines is a good option. Biodiesel fuels have similar properties with diesel fuels, so they can be used in diesel engines. Indeed, biodiesel fuels are generally made from animal fats, from renewable and easily available vegetable oils [9].

Despite the advantages of diesel engines, emission values are still a threat for the environment. In this context, when it is considered that diesel engines will be common in the near future, improvements should be made. Because, there will be 2.5 billion cars in 2050, and in the near future it will not be possible to replace all internal combustion engine vehicles with battery powered electrical vehicles [10]. In this regard, emission values should be under the given standards. Therefore, alternative systems should be considered to reduce exhaust emissions. The system, which can provide this reduction, is after treatment system. Reduction of particulate matter and nitrogen oxides is very difficult. So, generally two after treatment systems are used for the reduction of the emissions [11].

Biodiesel fuels are oxygen-containing fuels and can be used to increase combustion efficiency in diesel engines. For efficiency assessment of the engines, thermodynamic analysis is necessary [12].

The first and second laws of thermodynamics are used for the analysis of engines. According to the first law of thermodynamics, it can be determined how much of the energy that enters the engine is converted into effective power or lost by the exhaust gases and the engine cooling system. But, the first law of thermodynamics does not give any idea about the qualities of these energies. The availability of these energies (useful work potential) can only be determined by the second law of thermodynamics. Furthermore, according to the second law of thermodynamics, it is also possible to determine the destruction of the exergy caused by irreversibility, which leads to a decrease in the thermodynamic efficiency of the engine. All this detailed information can only be reached through exergy analysis. Exergy analysis is an effective method, including the second and first laws of thermodynamics with principles of conservation of mass and energy, used in the design, analysis, and enhancement of thermal systems [13].

There have been some studies in the literature, such as exhaust emissions, particulate matter, after treatment systems and trials to reduce harmful substances in exhaust emissions. Nakakita [14] conducted a study on the development trends in combustion and treatment systems for new generation High-Speed Direct Injection (HSDI) diesel engines. The torque and power densities reached 160-170 Nm/l and 50-60 kW/l, respectively. The developments of common-rail (CR) injection systems, high-efficiency after treatment devices (such as the catalysts and Diesel Particulate Filter (DPF)), and advanced electronic control systems were considered as major technical backgrounds of the progress in HSDI diesel engines [14].

Alkemade and Schumann [15] examined engines and their exhaust emissions for future automotive technology. It was envisaged that safe, clean and efficient engines became more important in modern societies where we had greater mobility. The exhaust gas of gasoline engines was mainly treated with “Three Way Catalysts” (TWC). The CO, NO_x and hydrocarbons were converted by the catalyst into chemical gases such as CO_2, H_2O and N_2. The heavy-duty diesel engine exhaust could be treated with ammonia by Selective Catalytic Reduction (SCR) to reduce NO_x in addition to the catalytic oxidation of CO and hydrocarbons. The particulate emissions of the diesel engines were removed by Diesel Particulate Filters (DPF). The oxidation catalyst and the DPF system were controlled by temperature, pressure and particle sensors [15].

Soltic et al. [16] studied about the effects of mineral diesel fuel, gas-to-liquid fuel, rapeseed methyl ester, neat soybean and neat rapeseed oil on injection, combustion, efficiency and pollutant emissions of a compression ignition heavy duty engine operated near full load and equipped with a combined exhaust gas after treatment system (oxidation catalyst, particle filter, selective catalytic NO_x reduction). According the experiments, the critical NO_x emissions were high (even behind the exhaust gas after treatment systems) for oxygenated fuels in the event of the engine not being recalibrated for the fuel. Gas-to-liquid and the oxygenated fuels showed lower emissions for some pollutants and higher efficiency after recalibration [16].

Kim et al. [17] analyzed the performance, emission characteristics and particle size distribution of the engine they used in their study of a Common Rail Direct Injection (CRDI) diesel engine equipped with heated catalytic converters and catalysed particulate filter (CPF). According to the results, the use of a blended fuel of bio-diesel and bioethanol (BD15E5) was more effective in reducing particle number and particle mass compared to the use of BD20 fuel [17].

Rounce et al. [18] tested ultra-low sulphur (ULS) diesel and biodiesel (rapeseed methyl ester (RME)) without and with after treatment system (diesel oxidation catalyst (DOC) and diesel particulate filter (DPF)). In this context, they found that RME combustion produced low unburned total hydrocarbon (THC), carbon monoxide (CO) and particulate matter (PM) emissions, but increased NO_x emissions [18].

Mokhri et al. [19] examined soot filtration in Diesel Particulate Filter (DPF) and soot cake. According to this study, the soot cake increases the pressure drop. It also increases the filtration efficiency. During the regeneration process, the soot is removed to prevent the DPF from clogging [19].

According to Marcano et al. [20], DOC and DPF reduced the gas and solid pollutants obtained from MoS_2 (Molybdenum disulphide) added oil. A resistance test of 100 hours (equivalent to 10,000 km) proved the stability of the catalytic system and the suitability of the post-commercial catalysts to cope with the emission changes induced by the addition of nano additives to the oil matrix [20].

Oravisjärvi et al. [21] analyzed the regional precipitation of diesel particles into human lungs and the chemical composition of the inhaled particles. They used the off-road diesel engine with a DPF or a selective catalytic reduction (SCR) unit and without any exhaust after-treatment system. Approximately, 85-95% of the measured particles were in ultra-fine size and 53-84% of these ultra-fine size were nanoparticles. It was found that DPF system effectively removed the particles and the total number of particles precipitated in the lungs was generally lower when using DPF [21].

Feng et al. [22] studied on the nitrogen dioxide (NO_2) and particulate matter (PM) emissions of the 4-cylinders, intercooled, turbocharged diesel engine with using particulate oxidation catalyst (POC). According to test results, POC significantly increased the NO_2/NO_x ratio at medium and high loads [22].

Huang et al. [23] researched effects of fuels, engine load and exhaust after-treatment on a heavy-duty (6.4 L) diesel engine fuelled with three different fuels at various loads (600 and 900 kPa BMEP). The fuels were ultra-low sulphur diesel (ULSD), Swedish low aromatic diesel, and neat soybean biodiesel fuels. It was found that Swedish diesel and biodiesel fuels reduced the emissions [23].

Mori et al. [10] examined the effect of biodiesel fuel and engine oil on exhaust emission of the diesel engine. In this context, when BDF100 biodiesel was used, particle number concentration (PN) decreased [10].

Wei et al. [24] experimentally investigated the reduction of unregulated emissions (including unburned methanol, formaldehyde, formic acid, 1,3-butadiene, benzene and toluene) of diesel methanol dual fuel (DMDF) by different treatment devices. They tested the DMDF fuelled engine under 25%, 50%, 75% and full load with the same injection parameters at 1660 rpm and 2090 rpm. The engine was tested with and without after-treatment devices (single diesel oxidation catalyst (DOC) and DOC coupled with particulate oxidation catalyst (DPOC)). It was found that the conversion efficiency of the DPOC was higher than that of the single DOC. Uniform DOC could significantly reduce emissions of unburned methanol, 1,3-butadiene and formic acid from the DMDF engine at medium and high loads, especially when the exhaust gas temperature was relatively high [24].

Praveena and Martin [25] conducted a study on various purification techniques to reduce NO_x emissions in a CI engine by using after treatment methods. It was found that hybrid

Selective Catalytic Reduction (SCR) such as Cu-SCR + Fe-SCR, SCR + LNT reduced fuel consumption and increased catalytic activity at low temperatures [25].

Zhang et al. [26] worked on the particulate matter emissions including particle count (PN), particle mass (PM), particle size distributions, and nitrogen compound emissions of the diesel engine with DOC, catalytic diesel particulate filter (CDPF) and SCR [26].

In the literature, there are also some studies about advanced thermodynamic analyses and emission assessments of diesel engines fuelled with various fuels. Park et al. [27] examined exhaust emissions and nanoparticles of 20% the biodiesel blend (BD20) and the diesel fuelled diesel engine. At high load, maximum torque of the BD20 was lower than diesel fuel. But, the CO and THC emissions of BD20 were lower, NO_x emissions were higher than diesel fuel. When BD20 is used, the total number and size of nanoparticles could be decreased. On the other hand, the fuel consumption and particle numbers were reduced using exhaust gas recovery on the engine [26]. Caliskan and Mori [28] worked on Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF) after treatment systems integrated 3L diesel engine fuelled with 20%, 50% and 100% the biodiesel fuels (BDF20, BDF50, BDF100, respectively) and the JIS#2 diesel fuel. The fuels were experimentally analyzed at 100 Nm, 200 Nm and full load (294 Nm). In addition, the engine speed and cooling water temperature were constant at 1800 rpm and 80°C, respectively. It was found that the BDF100 fuel had maximum efficiency. The use of DOC was effective to reduce the fuel consumption of the BDF50 fuel; besides DOC and DOC + DPF were effective for the BDF100 fuel. In another study, Caliskan and Mori [29] studied on thermodynamic, environmental and economic effects of diesel and biodiesel fuels on exhaust emissions and nano-particles of a diesel engine. The most of the exhaust emissions were proportional to engine load (except NO_x). The maximum CO_2 and NO_x emissions ratios were generally found for the BDF100 biodiesel fuel. But, the minimum rates were found for the JIS#2 diesel fuel. The fuel consumption from maximum to minimum at all engine loads was as BDF100>BDF50>BDF20>JIS#2. The sustainability ranking of fuels was as BDF100>BDF50>BDF20>JIS#2. The thermoeconomic and exergoeconomic parameter rate from maximum to the minimum was as JIS#2>BDF20>BDF50>BDF100.

The objective of this study is to investigate the exhaust emissions and nanoparticles of diesel and 100% biodiesel fuelled diesel engine in terms of energy, exergy, sustainability, thermoeconomic, exergoeconomic and various environmental analyses. The main aims of this study can be expressed as follows:

- Examination and comparison of the effects of different fuels to see the effects on diesel engine efficiency, particulate matter, sustainability, etc.
- Tuning the engine under different engine loads to see the torque effects.
- Using the Scanning Mobility Particle Sizer (SMPS) to measure the size distribution of the engine exhaust particles.
- Assessing the data of the CO, CO_2, NO_x, HC exhaust gases, soot, particle numbers (PN), fuel consumptions, etc.
- Researching the emissions by using Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and DOC+DPF after treatment systems.

2. SYSTEM DESCRIPTION

The main equipment of the system is composed of diesel engine, measurement devices, diesel fuel, biodiesel fuel, Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF) after treatment systems.

The first starting point of the system is the fuel tank. The fuel is filled into the tank. The fuel containing 100% biodiesel is called as BDF100 and it includes the waste cooking oil. The other fuel is the Japanese Industrial Standard Diesel No:2 which is called as JIS#2. The biodiesel fuel and the diesel fuel are the fuels used in this work. The gas pipes are then opened to initiate the calibration of the emission measuring devices. The coolant temperature of the engine is fixed at 80°C and the measurement points of the running engine are set at 100 Nm, 200 Nm, and 294 Nm at 1800 rpm (peak performance). Also, the Scanning Mobility Particle Sizer (SMPS) is used to measure the nano-particles and exhaust emissions of the fuels. The values are kept constant when the fuel temperature reaches 40°C and the boost temperature reaches 50°C. For without after treatment system, every fuel is tested five times at 100 Nm, 200 Nm and 294 Nm, respectively. However, for after treatment system, every fuel is tested five times at 100 Nm and 200 Nm. Since this process is applied separately for each fuel, a total of 15 tests are made for without after treatment system and 10 test are made for after treatment system. The average values of these tests are taken into account for the analyses.

In this regard, the pre-conditioning cycle is made to create a steady state. This is done due to the formation of the soot in order not to separate the obtained data. The pre-conditioning cycle is performed for 30 minutes, then, the measurement is performed. The Exhaust Gas Recirculation (EGR) is not used when the system is running. The system configuration is shown in Figure 2.1.

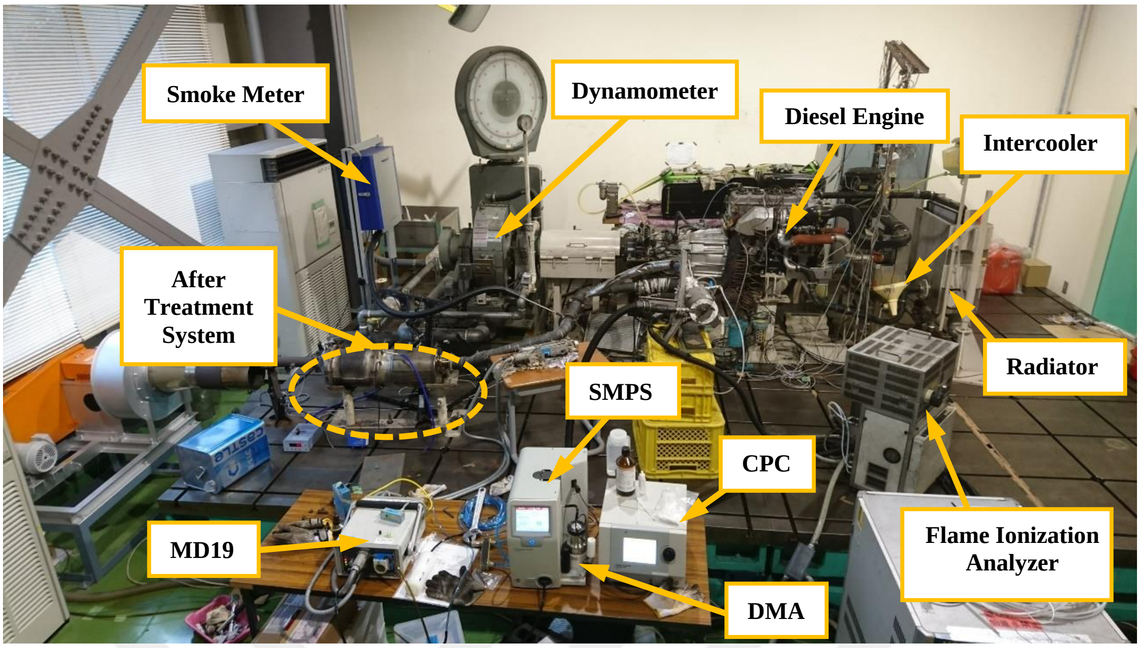


Figure 2.1. System configuration

2.1. Engine

The characteristics of the engine used in this study are as follows: 4-cylinder, 3L, turbocharged, intercooled Mitsubishi Fuso diesel engine. The diesel engine unit mainly includes Exhaust Gas Recirculation (EGR), Common Rail System (CRS) and water cooler. However, EGR is not used in this study. The features of the diesel engine are given in Table 2.1. Also, the layout of the diesel engine is shown in Figure 2.2.

Table 2.1. Features of the diesel engine [10]

Engine	Inline-4 Direct Injection Turbocharged and Intercooled
Engine Model	4M42(2AT3)
Valve Train	DOHC 16 valves
Combustion	DI (Direct Injection)
Displacement	2997 cc
Compression Ratio	17.5
Bore x Stroke	95.0 mm x 105.0 mm
Fuel Equipment	Common Rail type
EGR	With cooler
Max. Power	96 kW (130PS)/3200 rpm
Max. Torque	294 Nm/1800 rpm

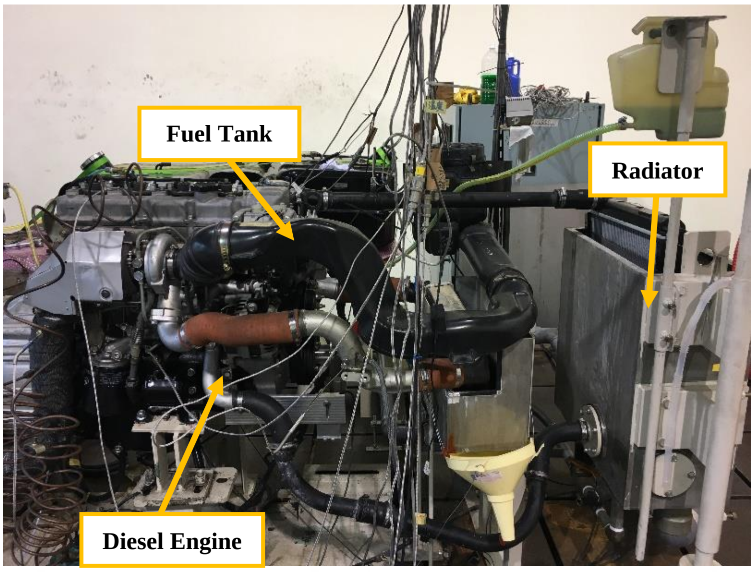


Figure 2.2. Layout of the diesel engine

2.2. After Treatment Systems

The major hazardous substances in the diesel exhaust gasses are particulate matter (PM), NO_x, CO and HC. Usually, the CO and HC can be purified by Diesel Oxidation Catalyst (DOC), but some new technologies are urgently needed to purify PM and NO_x [14]. Generally, after treatment systems are used for diesel engines. Diesel engines use diesel fuels with higher energy density per unit volume of fuel than gasoline. Moreover, they work higher torque for similar sized engines and bigger compression ratios than gasoline.

Especially in big cities, environmental protection has become an important issue due to the increased air pollution. Emission control regulations have been introduced in all industrialized countries, so that the emissions of vehicles operating with internal combustion engines are reduced with the regulation [15]. Therefore, reducing engine exhaust emissions has become necessary for better environment. In this regard, after treatment systems are required to control the emissions of diesel engines.

DOC and Diesel Particulate Filter (DPF) are used for after treatment system. DOC can be used alone or with DPF. The schematic layout of the after treatment system with DOC and DPF is given in Figure 2.3.

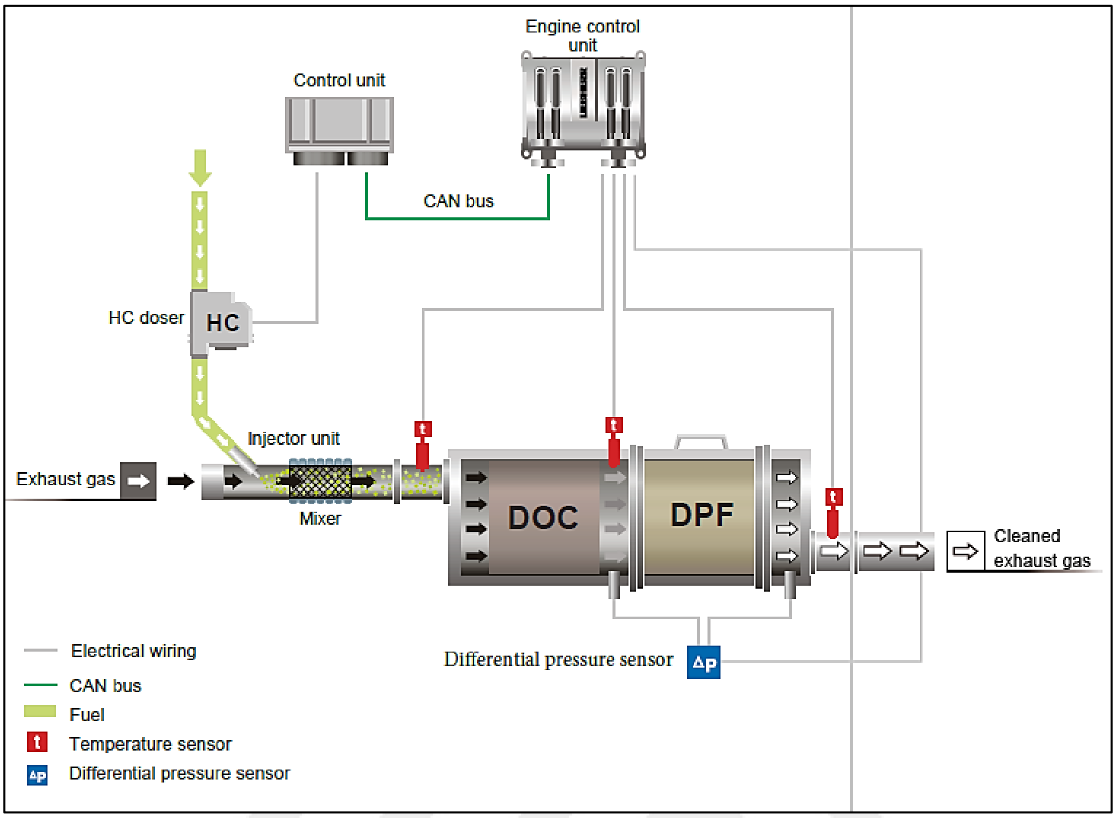


Figure 2.3. The schematic layout of the after treatment system with DOC and DPF [30]

The HC doser in Figure 2.3 (fuel dosing unit) refers to; if the temperatures are not high enough for passive regeneration of the particulate filter, the thermal management system actuates the dosing unit and a precisely metered quantity of fuel is injected into the exhaust gas in front of the DOC [30].

The utilizations of DOC and DPF are as follows;

a) DOC only: In this method, the DOC is used alone. DOC system cleans the CO and debris from unburned fuels by oxidation of these components to CO_2 and H_2O. Moreover, nitrogen (N) and nitrogen monoxide (NO) are oxidized into nitrogen dioxide (NO_2) in DOC. The schematic view of the DOC is given in Figure 2.4.

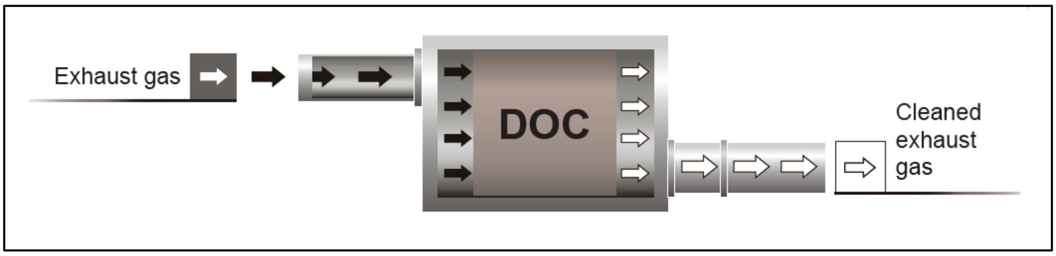


Figure 2.4. The schematic view of the DOC [30]

b) DPF only: Like DOC, DPF can be used alone. But, DPF is generally used with DOC. Because, this may be more effective in reducing exhaust emission values. DPF is a kind of filter made from special materials like SiC or cordierite to trap the particles. The schematic view of the DPF is as shown in Figure 2.5.

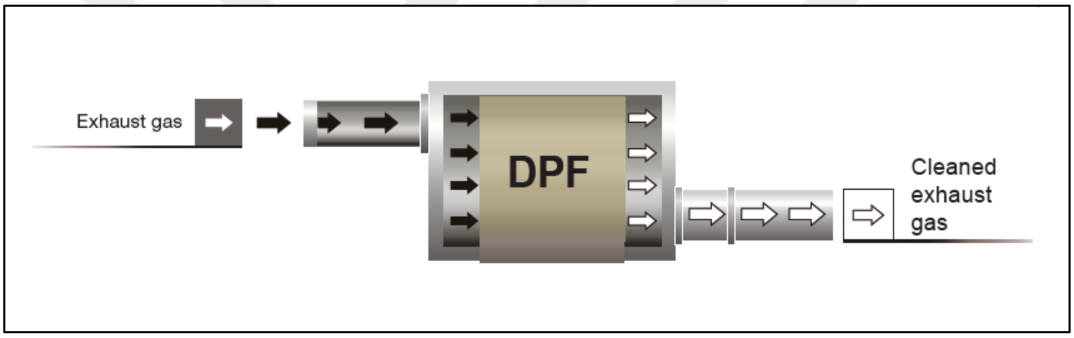


Figure 2.5. The schematic view of the DPF [30]

c) DOC+DPF: The DOC and DPF can be used alone, but they can also be used in conjunction together. In this method, DOC and DPF are used together. According to this method, the exhaust gas is forced to pass the poriferous walls of the filter, which trap the particulates at the end of enclosed channels. Therefore, DOC + DPF can also reduce the particles and exhaust emissions [28]. The schematic view of the DOC+DPF is shown in Figure 2.6.

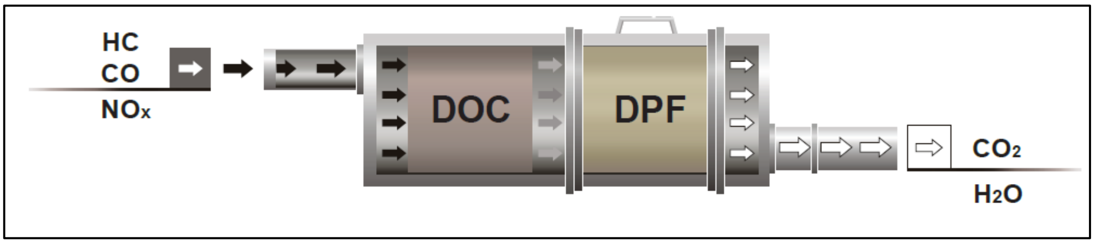


Figure 2.6. The schematic view of the DOC+DPF [30]

When the DOC performance fails to meet the applicable regulations in terms of particulate emissions, the DPF is used. Thanks to the particle filter, more than 90% of the particles can be stopped.

2.2.1. Diesel Oxidation Catalyst (DOC)

Diesel oxidation catalyst (DOC) takes its name from the abundance of oxygen in the diesel exhaust, with the ability to promote oxidation of the exhaust gas components. When subjected to an oxidation catalyst, unregulated emissions such as gas-phase hydrocarbons (HC), carbon monoxide (CO), organic fraction of diesel particulates (SOF) and aldehydes or PAHs can be oxidized to harmless products. Thus, these emissions can be controlled using DOC. The reaction mechanism on the diesel oxidation catalyst is explained by the presence of active catalytic sites on the surface of the catalyst carrier. At this point, this mechanism has the ability to adsorb oxygen. The catalytic reaction proceeds as follows: Firstly, oxygen is attached to a catalytic site. Then, some reactants, such as hydrocarbons and CO, spread to the surface and react with the bound oxygen. Finally, reaction products such as water vapor and CO_2 are spread to the mass of the exhaust gas coming from the catalytic region [31].

DOC is usually used in order to overcome the CO and HC emissions. It uses a chemical process to convert the harmful pollutant such as CO from diesel engine exhaust gas to less toxic CO_2. Also, as a result of the HC reaction, H_2O is formed. The DOCs are usually honeycomb-shaped configurations coated in a catalyst. The catalyst is a chemical substance that can increase the rate of the reaction. Also, catalyst is not consumed in the catalyzed reaction. Thus, these exhaust emissions can continue to catalyze the other reaction. The DOC can also be used to regenerate the DPF. The general layout of the DOC used in this study is showed in Figure 2.7, while the overview and features of DOC are given in Figure 2.8.

Figure 2.7. General layout of the DOC used in this study

Diesel Oxidation Catalyst (DOC)	
	✓ Old technology ✓ Little black carbon removal ✓ Little ultrafine PM removal ✓ Does not remove lube oil ash

Figure 2.8. Overview and features of the DOC [32]

2.2.2. Diesel Particulate Filters (DPF)

DPF device is able to filter out more than 90% of soot particles. DPFs are technically the most appropriate solution for reducing PM [33]. While the diesel particulate filter allows exhaust gases to pass through the system, it is designed to accumulate solid-liquid particulate matter emissions [34]. Generally, a post combustion PM control system consists of porous metal or ceramic filter. It is desired that the filter has a low pressure decrease and a high operating capacity [35]. Today, commercialized diesel particulate filters are made from silicon carbide, cordierite or metal.

In this study, DPF material is composed of silicon carbide and cordierite. The accumulation efficiency of these various filters ranges from 30-90% by mass, but most diesel particulate filters achieve over 99% when expressed as extremely fine particle counts [36]. The SiC and cordierite diesel particulate filters are shown in Figure 2.9 and the general layout of the DPF used in this study is given in Figure 2.10. Also, the overview and features of the DPF are given in Figure 2.11.

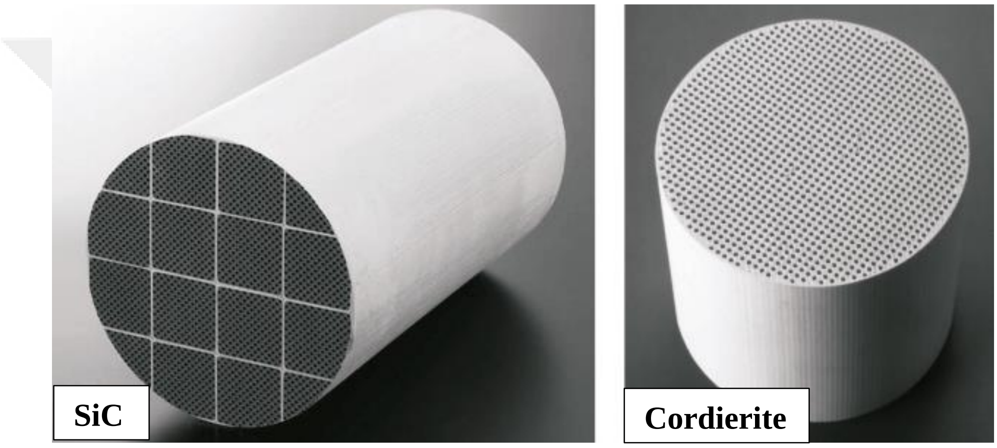


Figure 2.9. SiC and cordierite diesel particulate filters [37]

Figure 2.10. General layout of the DPF used in this study

Diesel Particulate Filter (DPF)	
	✓ New technology ✓ Used on all new trucks since 2007 ✓ >85% black carbon removal ✓ >85% ultrafine removal ✓ >85% lube oil ash removal

Figure 2.11. Overview and features of the DPF [32]

Commonly, the exhaust temperature is increased by adjusting the throttle, the gas temperature is increased by burner and the particulate combustion temperature is reduced by catalyst. So that the accumulation of particles is burned as soon as possible, the pressure loss is recovered, the function of the filter is restored, and the filter is regenerated [37]. The comparison of the DOC and DPF are given in Figure 2.12, while the DOC+DPF specification is shown in Figure 2.13. In addition, the schematic layout of the after treatment system used in this study can be seen in Figure 2.14.

DOC	DPF
	
It is the first component to receive the engine exhaust.	Generally, it is used in conjunction with that is the second component, the DOC.
It protects the DPF.	Hydrocarbon liquids or vapor can interfere with the DPF’s ability to trap and remove particulate matter, so manufacturers route the exhaust through the DOC first, then into the DPF.
It is a flow-through device that forces exhaust onto a honeycomb ceramic structure coated with precious metal.	It forces the exhaust gases to flow through porous channel walls, trapping and holding the remaining PM.
CO, HC and Soluble Organic Fraction (SOF) of diesel PM are oxidized to CO_2 and H_2O. $CO + 1/2O_2 \rightarrow CO_2$ [Hydrocarbons] + $O_2 \rightarrow CO_2 + H_2O$ [SOF] + $O_2 \rightarrow CO_2 + H_2O$	The captive particles on the DPF filter element are oxidized (burned) by a continuous cleaning process called passive regeneration.

Figure 2.12. Comparison of the DOC and DPF

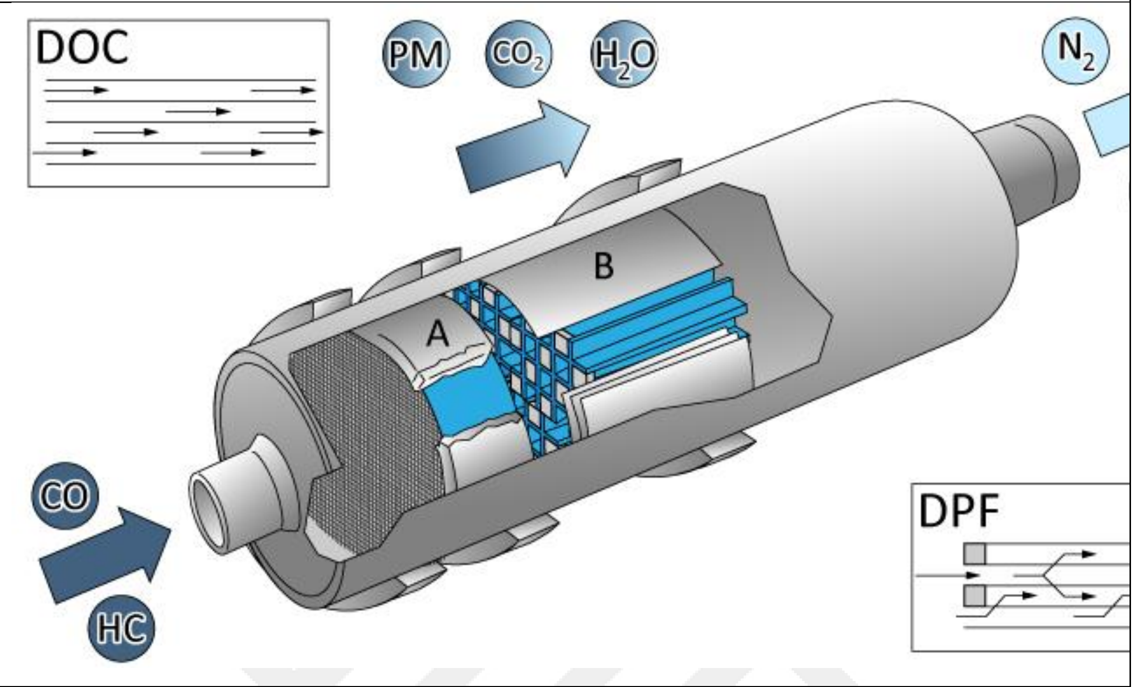
DOC+DPF

The exhaust flows out of the engine and it passes through the DOC and then into the DPF where PM is collected on the walls of the DPF. Then, the collected PM is oxidized to remove it from the DPF. This is known as regeneration.
When operating conditions maintain sufficient exhaust temperatures, the DPF is continually self-regenerating. This is known as passive regeneration and results in clean exhaust out of the tailpipe. On very infrequent occasions, an active self-regeneration is required to remove a build-up of PM in the DPF, due to insufficient exhaust temperatures

Figure 2.13. DOC+DPF specification [38]

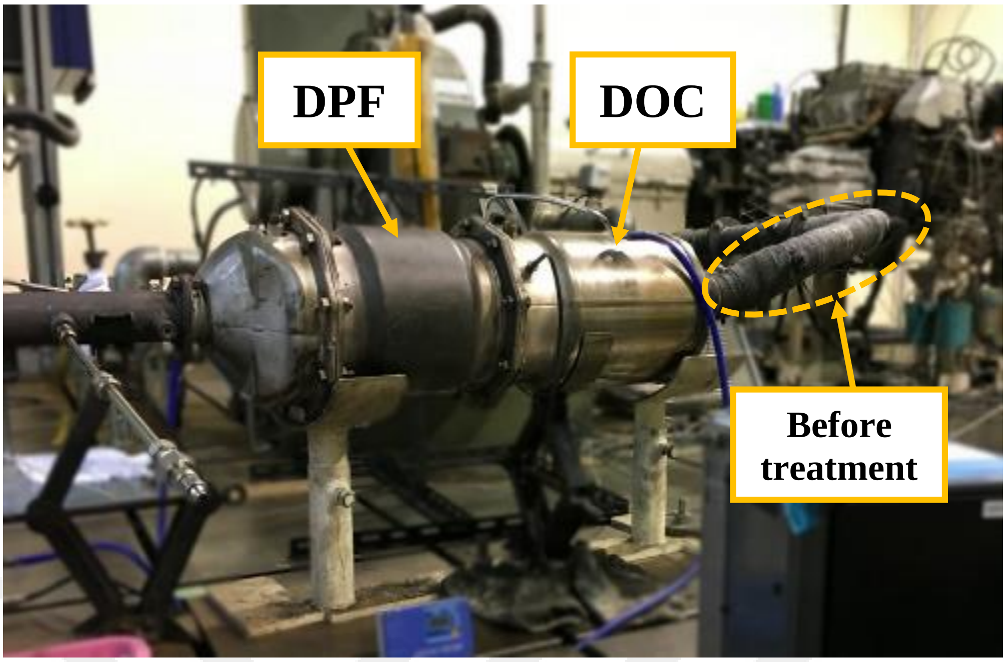


Figure 2.14. The schematic layout of the after treatment system used in this study

2.3. Measurement Equipment

2.3.1 Exhaust Emission Analyzer

In this system, Horiba Mexa-9100F model is used as exhaust emission analyzer. It can measure the THC, CO, CO_2, NO_x emissions with 900 ms response time. Firstly, the gas cylinder units used for exhaust gas measurement are opened. When it is ensured that the types of gas to be measured are open, the exhaust gas units are prepared separately. The data from the system is obtained from the screen of this exhaust emission analyzer. In addition, this data can also be seen automatically from the control panel display. In this equipment, THC, CO and CO_2 gases are measured as parts per million (ppm), while CO_2 is measured as percentage (%). The general layout of the exhaust emission analyzer is given Figure 2.15.

Figure 2.15. General layout of the exhaust emission analyzer

In addition, the detailed information and schematic of the exhaust emission analyzer for THC, NO_x, CO and CO_2 gases are explained below.

2.3.1.1. Total Hydro Carbon (THC) Meter

It is an instrument that measures the amount of hydrocarbons in the exhaust gas using the hydrogen flame ionization method (FID method). The THC in the exhaust gas is displayed in ppm on the display part. THC display unit is shown in Figure 2.16.

Figure 2.16. THC display unit

2.3.1.2. NO and NO_x Display Unit

It is an instrument that measures the amount of nitrogen oxide in the exhaust gas using the chemiluminescence method (CLD method). NO_x in the exhaust gas is displayed in ppm. Also, when measuring NO, it is possible to measure by switching the red circle in Figure 2.17.

Figure 2.17. NO and NO_x display unit

2.3.1.3. CO and CO_2 Display Unit

It is an instrument that measures the amounts of carbon monoxide and carbon dioxide in the exhaust gas using the non-dispersive infrared absorption method (NDIR method). CO in the exhaust gas is displayed in ppm on the display part in Figure 2.18, and CO_2 is displayed in vol% on the display part.

Figure 2.18. CO and CO_2 display unit

2.3.1.4. Gas Cylinder Units

These gas cylinders are used to measure the THC, NO_x, CO and CO_2 emission values. The gasses in these tubes are necessary for the calibration of the gas analyzer. The figure below (Figure 2.19) shows the general layout of the gas cylinder units;

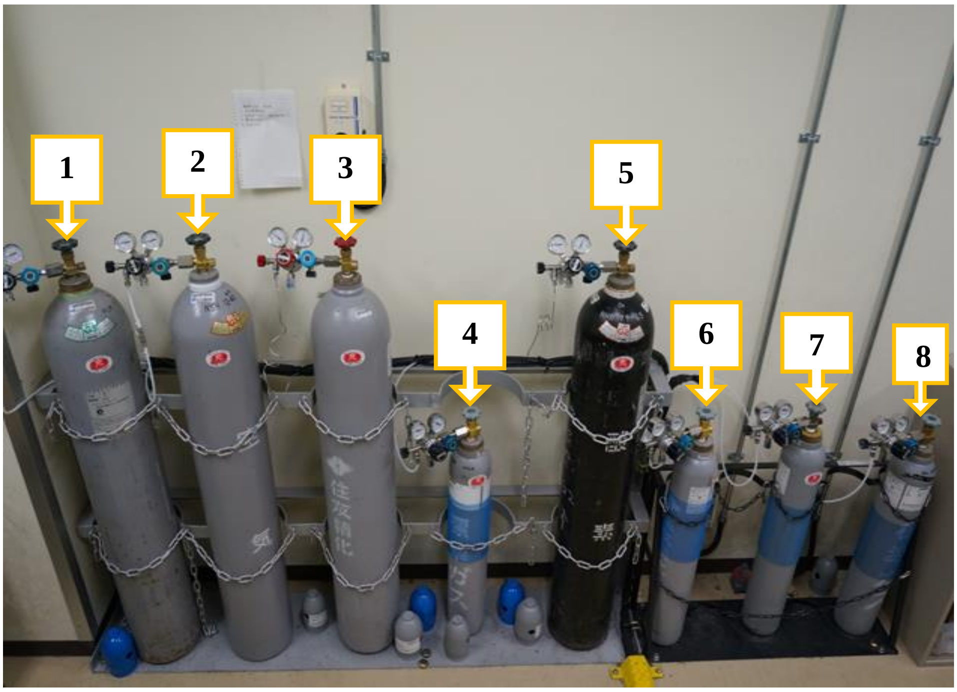


Figure 2.19. General layout of the gas cylinder units

1) N_2 gas cylinder (99.9995%)
2) Air gas cylinder
3) H_2 / He gas cylinder (40.1%)
4) CO gas cylinder (975 ppm): Comparative gas of CO
5) O_2 gas cylinder (more than 99.999%): For ozone generation
6) CO_2 gas cylinder (15.60%): Comparative gas of CO_2
7) NO gas cylinder (977 ppm): Comparative gas of NO_x
8) C_3H_8 gas cylinder (162.5 ppm): Comparative gas of HC

2.3.2. Smoke Meter

The smoke meter is a AVL 415S model filter-type smoke meter. It is used for measuring the soot content in the exhaust of diesel and gasoline direct injection engines. The variable sampling volume and thermal exhaust conditioning assures a wide applications range, e.g. measurements during engine development or DPF calibration. A defined flow rate is sampled from the exhaust pipe through a clean filter paper in the instrument. The filtered soot causes blackening on the filter paper which is detected by a photoelectric measuring head and evaluated in the microprocessor to calculate the result in Filter Smoke Number (FSN) or mg/m^3 [39].

The measuring principle of smoke meter is as follows: Due to the variable sampling volume, the instrument can be used many engines. When determining the soot content, the paper blackening and the volume of the exhaust drawn through the filter paper over the effective sampling length are considered [39]. The smoke meter used in this study is shown in Figure 2.20 and its measuring principle is illustrated in Figure 2.21, while the specification of the smoke meter is tabulated in Table 2.2.

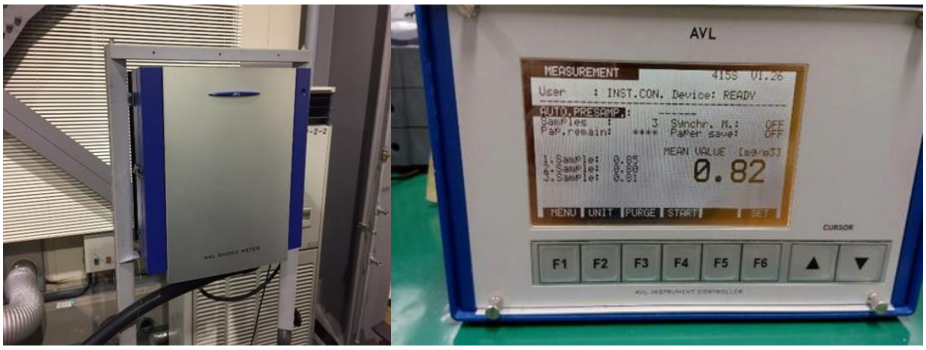


Figure 2.20. Smoke meter used in this study

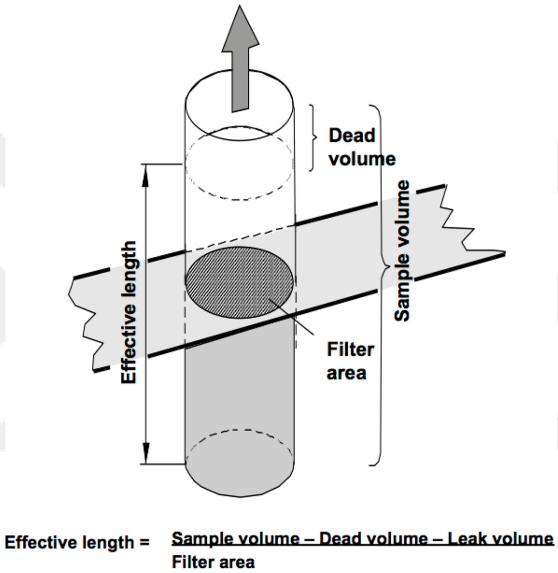


Figure 2.21. Measuring principle of smoke meter [38]

Table 2.2. Specification of the smoke meter [39]

Measurement principle	Measurement of filter paper blackening
Measured value output	FSN (filter smoke number) or mg/m³ (soot concentration)
Measurement range	0 to 10 FSN
Detection limit	0.002 FSN or ~ 0.02 mg/m³
Exhaust pressure ranges	(-300*) -100 to 400 mbars (-500*) -200 to 750 mbars with the special sampling option 0 to 3000 mbars with the high-pressure option (*) with activated altitude simulation
Resolution	0.001 FSN or 0.01 mg/m³
Maximum exhaust temperature	600 °C with standard 340 mm sample probe (800 °C with 780 mm long sample probe)
Power supply	100 – 115 VAC or 230 VAC, 50/60 Hz
Power consumption	700 VA
Interfaces	2 serial RS232 interfaces with AK protocol Digital via Instrument Controller 4210 1 Ethernet interface with InPort option installed with AK protocol
Compressed air (for compressed air option)	~150l/min during purge
Compressed air quality required	Grades 1.1.1 to 1.4.1 according to ISO 8573.1:2001(E) Recommended connection pressure on the AVL Smoke Meter: 5 to 8 bars at the measurement device input
Sample flow	~10 l/min
Weight	<40 kg
Repeatability	Standard deviation 1 s = ± (0.005 FSN + 3 % of the measured value @ 10sec intake time)
Ambient conditions	5 to 55 °C / max.95 RH; without condensation Sea level -500 to + 5000 m

2.3.3. Scanning Mobility Particle Sizer (SMPS)

One of the most widely used particle measuring devices is SMPS. Thanks to its size, the SMPS has an advantage in solubility of the concentration of the particles. However, the particle diameter derived from the SMPS is the equivalent diameter of the electrical mobility, which is different from the geometric diameter of the particles having complex shapes [40]. The model of the SMPS used in this study is TSI Model 3938. The size of the nanoparticle that it can measure is 4.61~162.5 nm.

The SMPS basically consists of two components; i) Differential Mobility Analyzer (DMA) for classification of particles by size and ii) Condensate Particle Counter (CPC) for the measurement of number concentration. There are two streams of motion in the DMA; aerosol particle flow and particle free air. The airflow provides lamination for the flow of aerosol particles [41]. SMPS uses electric mobility classification principle. In addition, SMPS measures particle size distribution and total particle number concentration of particles through CPC. The appearance of the SMPS used in this study is shown in Figure 2.22.

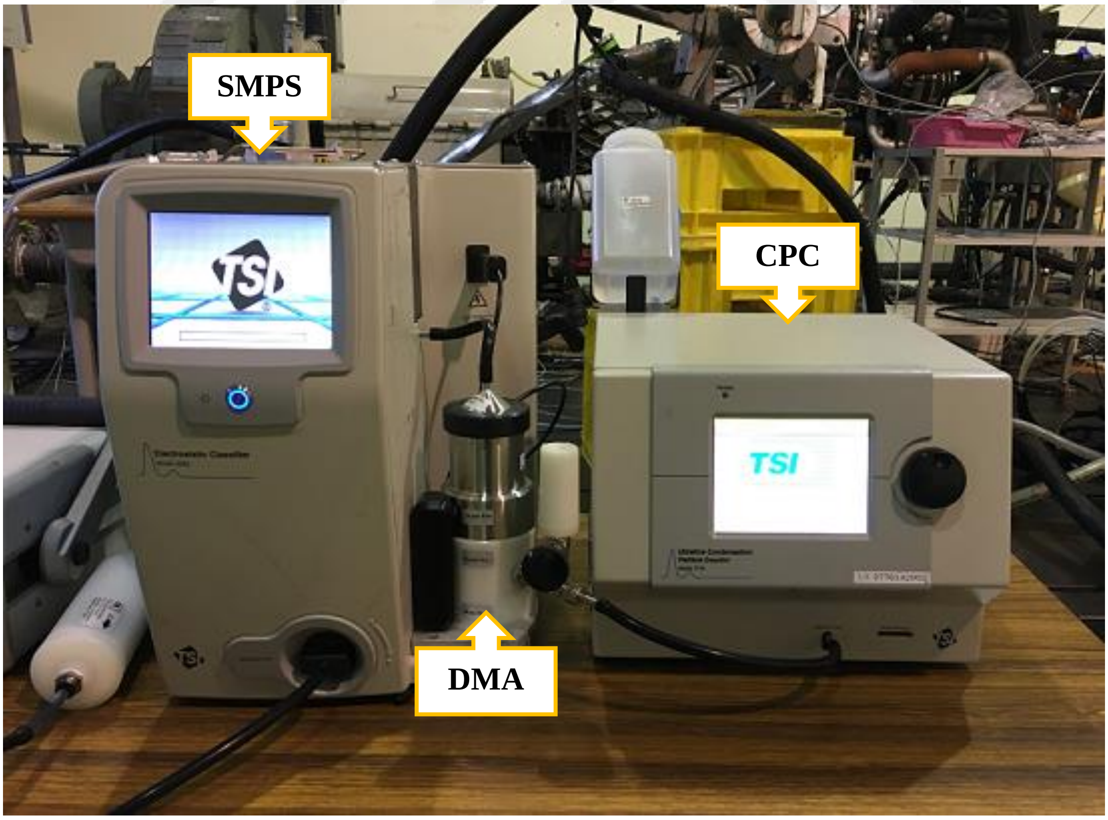


Figure 2.22. The appearance of the SMPS used in this study

Since SMPS has no lower detection limit, accurate measurement is possible. CPC makes use of the property of condensation that even if water vapor of alcohol falls below the dew point temperature, it becomes supersaturated water vapor without water drops if there is no core dust or particles.

By gradually increasing the voltage of the electrode rod, it enters the condensation particle counter from the one with the small particle size, and diffuses the sample air to the heated and vaporized alcohol, the condensation occurs and the particles can be detected with the laser It is measured in size.

2.3.4. SMPS Measurement Screen

Particle count and size data can be obtained with Aerosol Instrument Manager program. From the SMPS measurement screen, the particle size and number can be seen.

The Aerosol Instrument Manager software is used to collect sample data from the TSI and store the sample data in a file. Software can be used to display data on charts and tables or to view statistical information. Graphics and charts can be printed and exported with software for use in other applications. SMPS measurement screen is shown in Figure 2.23.

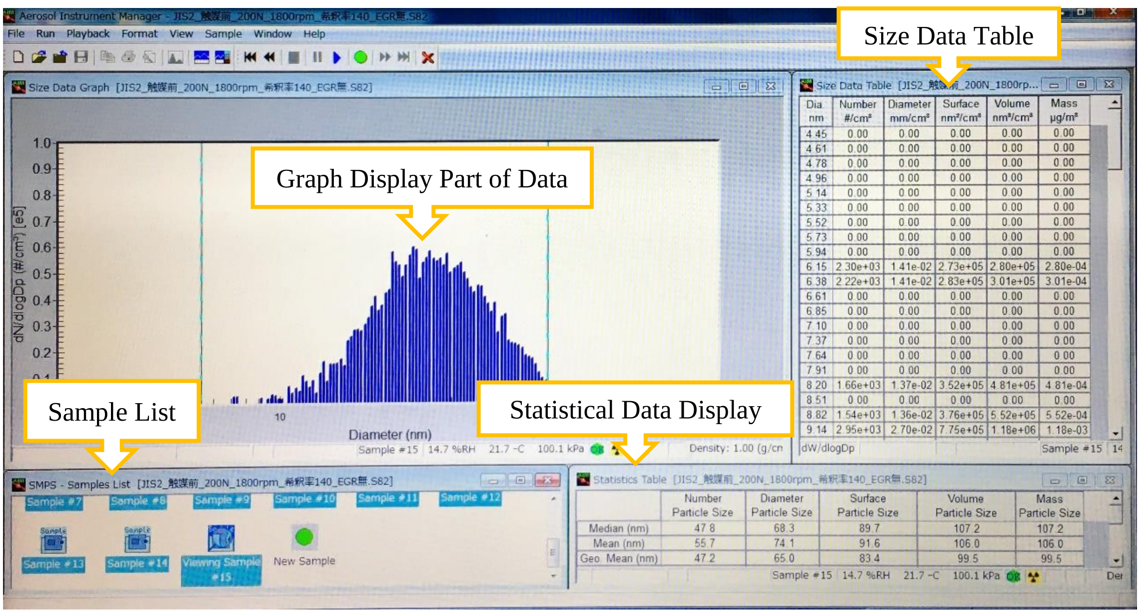


Figure 2.23. SMPS measurement screen

2.3.5. Differential Mobility Analyzer (DMA)

Differential Mobility Analyzer (DMA) is used in conjunction with SMPS to measure the particle size. DMAs are devices commonly used in the aerosol field to measure size distributions of charged particles. These tools are also used to produce aerosol standards from polydisperse aerosols: select particles with a certain (known) size [42].

Polydisperse particles stabilized in an equilibrium charged state are introduced by a neutralizer. A negative voltage of 0 to -10,000 V is applied to the electrode rod, and negatively charged particles are repelled to the outer wall. Zero-charged particles are discharged together with excess air. Only particles with a certain electric charge mobility with positive charge are attracted to the electrode and the dispersed particles pass from the slit. The schematic view of the DMA is given in Figure 2.24.

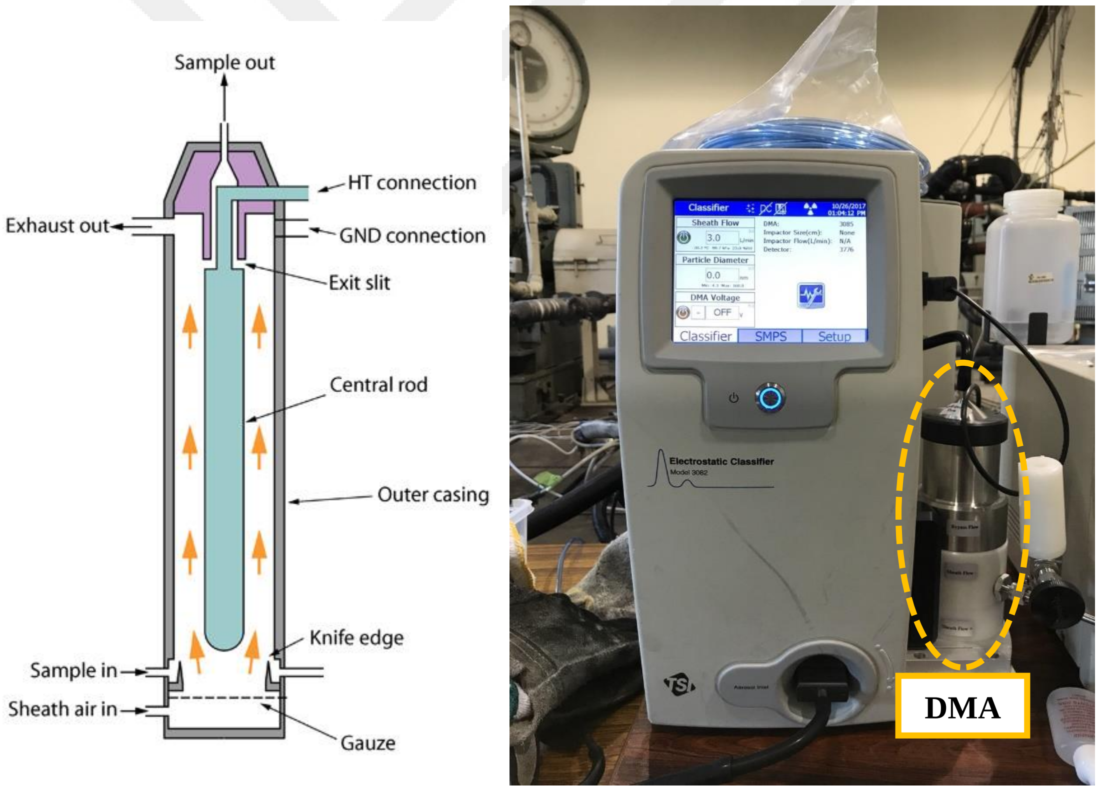


Figure 2.24. The schematic view of the DMA [43]

2.3.6. Ultrafine Condensation Particle Counter (CPC)

Concentration particle counters are often used in many applications, especially for the measurement of particle concentration, where the CPC is a significant feature of the large dynamic range [44]. Commercial CPCs can measure particles with diameters of about 3-

10 nm (depending on the CPC type). The measurement process consists of the growth of particles with a concentration of supersaturated vapor that can be detected by light scattering. A common CPC practice is the measurement of particles originating from combustion processes with particles having a maximum size of typically about 150 nm and a smaller minimum dimension, typically detectable by conventional CPCs [45]. The schematic view of the CPC used in this study is shown in Figure 2.25.

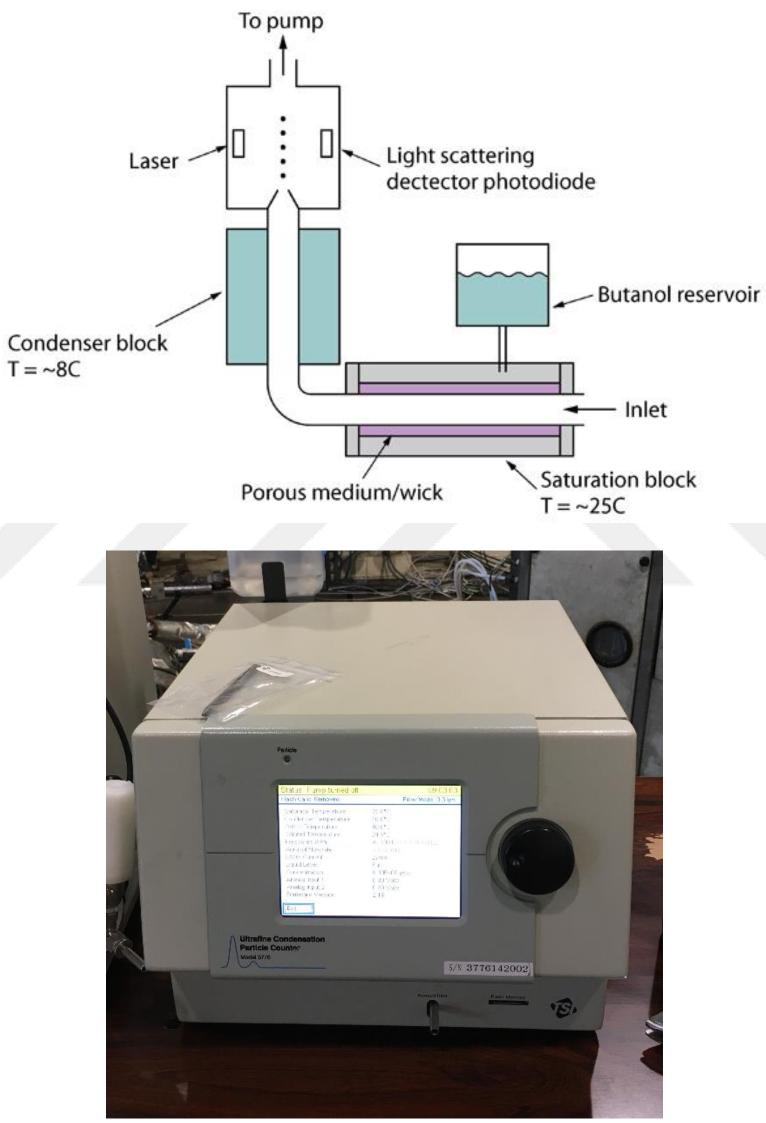


Figure 2.25. The schematic view of the CPC used in this study [43]

It consists of a cooled saturator part and a warmed condenser part. Particles aspirated from the inlet saturate with alcohol. As the alcohol diffuses from the tube wall to the tube center before the particles are heated, the particles become supersaturated and begin to condense. CPC detects particles that have become large droplets due to condensed growth in the optical section.

2.3.7. Flame Ionization Analyzer

The Horiba flame ionization analyzer is used to measure HC emission & particulate matter. The instrument uses the flame ionization detection to measure soot concentration. The soluble organic fraction can also be measured by splitting a sample gas line into a low-temperature line and high-temperature line. Then, it determines the difference in total hydrocarbon concentrations between the two lines [46]. The flame ionization analyzer used in this study is given in Figure 2.26.

Figure 2.26. Flame ionization analyzer used in this study

2.3.8. Fuel Consumption Analyzer

The Ono Sokki fuel consumption analyzer (with Ono Sokki digital flowmeter DF-2420) is used to measure instantaneous flow rate, cumulative flow rate, cumulative time, temperature, and pressure of the fluid [15]. The specific fuel consumption per minute is determined, and the fuel consumption rate is calculated from the specific gravity and torque. The fuel consumption analyzer used in this study is illustrated in Figure 2.27.

Figure 2.27. Fuel consumption analyzer used in this study

2.3.9. Digital Engine Tachometer

In this study, Universal Engine Tachometer CT-6520 model is used. It is used to select a large number of speed detectors according to measurement conditions such as detector position, engine type, etc. The multiplier circuitry feature can shorten the measurement period and thus improve measurement accuracy. The measurement data can be obtained with analogue, digital or pulse output. In addition, there are two pre-set r/min settings for data comparison and alarm function [44]. The engine tachometer used in this study is given in Figure 2.28.

Figure 2.28. Engine tachometer used in this study

2.3.10. Dilution System for Particle Measurement (DSPM)

The dilution system for particle measurement includes two separate components: (i) Matter Engineering (MD19-2E) Rotating Disk Diluter, and (ii) Matter Engineering (MD19-2E) Self Contained Device. There are two separate gas channels: the raw gas channel and the diluted measurement channel. The rotating disc is placed in front of the two gas channels and thanks to the gaps the small quantities of aerosol are transported from the raw gas channel to the measuring channel. The ratio of raw gas dilution is a linear function of the void volume, the number of hollows, the rotational frequency and the flow in the diluted gas channel [48]. The Dilution System for Particle Measurement (DSPM) used in this study is given in Figure 2.29, while the dilution principle layout is shown in Figure 2.30.

Figure 2.29. Dilution system for particle measurement used in this study

Figure 2.30. Dilution principle layout

2.3.11. Flow Control Unit

A mass flow meter measures the mass flow regardless of pressure and temperature. When mass is represented by flow, it is necessary to use units such as g/min and kg/min, which are different from the familiar units used for general fluid measurement. For this reason, it is common practice to use the volume flow at predetermined pressure and temperature conditions [49].

The flow rate of the air sent to the dilution device and the flow rate of the air sent into the SMPS are adjusted. In this system, model of the flow unit used in this study is MC-1A. The flow control unit used in this study is shown in Figure 2.31.

Figure 2.31. Flow control unit used in this study

2.3.12. Dynamometer

In this system, eddy current type dynamometer made by Meidensha is used. It is a device that measures the torque of the engine by joint with the engine shaft. By controlling with a control panel and applying a load, the engine generates torque, and the pointer of the dynamometer can measure the deflection torque. The dynamometer used in this study is shown in Figure 2.32 and its specifications is given in Table 2.3.

Figure 2.32. Dynamometer used in this study

Table 2.3. Specifications of dynamometer

	Standards/specifications
Model	PTW－DAD
Type	Eddy current formula
Maximum absorbing power	220 kW
Maximum speed	8000 rpm
Amount of cooling water	75 L/min (at 32℃)

2.4. Measurement and Control Board

Automotive technology continues to progress without break, as measures against exhaust gas for environmental protection, further reduction in fuel consumption, improvement in safety, etc. The automobile test environment is also advanced and complicated. So, innovative and facilitating methods may be needed to make the measurements easier. In this control board, the test contents are prepared abundantly as software parts and it can flexibly cope with test methods such as fuel consumption performance test, exhaust gas test and drive system test. The measuring part and the control part are managed by each dedicated CPU. Hence, the measurement and control with high accuracy and high response are possible. The operating process of the control board easily perform various setting operations such as scale value and alarm level of measurement data, display of test status, inspection of input/output signals, calibration, etc. on the same screen [50]. The measurement and control board used in this study is shown in Figure 2.33.

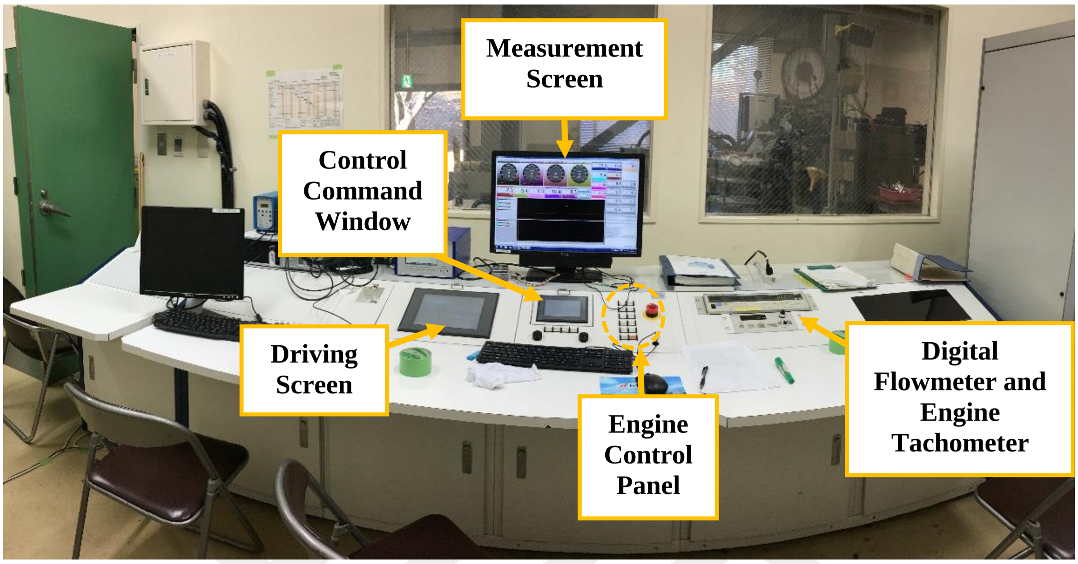


Figure 2.33. Measurement and control board used in this study

In the measurement screen, fuel-oil-water temperature, torque, engine rotation speed, intercooler temperature, exhaust temperature and pressure, soot content, soot concentration can be seen easily. Also, exhaust emission data, such as THC, CO_2, NO_x, can be obtained directly from the measurement screen.

2.5. Fuels

In Japan, there are two quality standards for diesel fuels: "Compulsory standard" as set out in the "Law on Quality Control of Gasoline and other Fuels" (Quality Assurance Act), and voluntary Japanese Industrial Standard (JIS) K 2204 "Diesel Fuel". JIS K 2204 consists of five class diesel fuels. The main difference between each class is the low temperature operability limits. These classes are as follows: No. 1, No. 2, No. 3, Special No. 1 and Special No. 3 (1S, 1, 2, 3 and 3S, respectively). The T90 distillation temperature, flash point, cetane index and viscosity will vary to provide flexibility to produce different grades for fuel manufacturers. No. 2 diesel fuel is generally used for highway vehicles (passenger cars, buses and trucks). Besides, Special No. 3 diesel fuel is used as the winter grade in Hokkaido and other cold climate areas [51]. In this study, the

JIS#2 diesel fuel and waste cooking oil based biodiesel fuel (BDF100) (fatty acid methyl esters) are used as fuels to operate the diesel engine. Cooking oil consists of edible vegetable oils derived from safflower, olives and peanuts. Cooking oil, sometimes edible oil added during the preparation of processed foods, is liquid at room temperature. In many regions thousands of years ago, people used the ingredients they had in their hands to produce oil for a variety of cooking purposes and processed vegetable oils. Cotton oil, grape seed oil, watermelon seed oil and other oils are accepted as ways to benefit from the seeds considered as waste. Some vegetable oils such as peanuts, some coconut and sunflower and olives oils are cold pressed. Most oil sources are not suitable for cold pressing because they leave undesirable elements in the oil [52]. We measured the specifications and characteristics of the fuels by the experimental methods in the Pollars Laboratory Co. Ltd. in Japan. The specifications of the fuels can be seen in Table 2.4.

Table 2.4. Specifications of the fuels

Fuel	Biodiesel	Diesel
Fuel code	BDF100	JIS#2
Density (kg/m^3)	882	831
Kinematic viscosity (mm^2/s)	6.270	3.743
Flash point (°C)	180	70
Acid number (mgKOH/g)	0.1495	0.0645
Cloud point (°C)	6	-1
Pour point (°C)	-7	-19

2.5.1. Density of Fuel Sample

The density of a substance, or rather the volumetric mass density, is the mass per unit volume. Fuel density is expressed in kilograms per cubic meter. The greater the fuel density, the greater the amount of fuel that can be stored in a given volume. The fuel density usually increases with increasing molecular weight of the fuel molecules. Also, fuel density generally increases with increasing molecular weight of the component atoms of the fuel molecules [50].

For the fuel density test, the water tank, which is used in this study, is filled with water and the water temperature is set at 15 °C. The water cooler cools the water and keeps it at 15°C. On the other hand, the fuel is placed in the test tube. This test tube is then placed in a water tank which is stationary at 15 °C. Then, the hydrometer is inserted into the test tube and floats over time. When it will be stable, the value is read and the density is obtained. The density test instrument is shown in Figure 2.34.

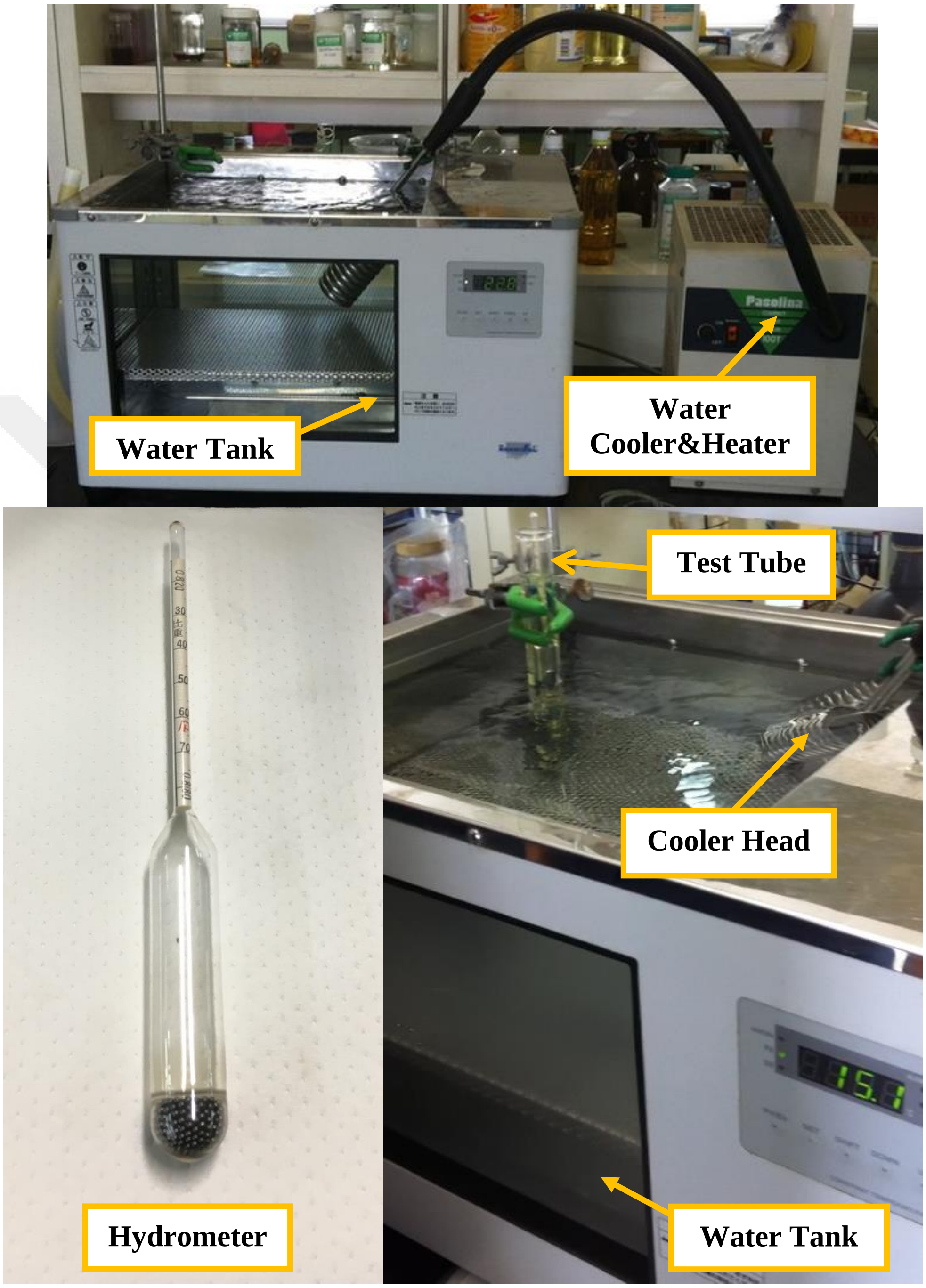


Figure 2.34. Density experiment device

2.5.2. Viscosity of Liquids

The viscosity of a liquid is a measure of its resistance to gradual deformation by shear stress or tensile stress. For liquids, it corresponds to the informal concept of thickness. Viscosity is a feature caused by collisions between neighbouring particles in a liquid moving at different velocities. When the fluid is forced through a tube, the particles which compose the fluid generally move more quickly near the tube's axis and more slowly near its walls; therefore, some stress (such as a pressure difference between the two ends of the tube) is needed to overcome the friction between particle layers to keep the fluid moving. For a given velocity pattern, the required stress is proportional to the fluid viscosity [53].

2.5.2.1. Fuel Viscosity

Fuel viscosity control is a technique to control viscosity and temperature of fuel for efficient combustion in diesel engines of motor vessels and generators of oil-fired power plants. Fuel's viscosity strongly depends on the temperature, the higher is the temperature the lower is the viscosity.

For the viscosity test of the fuel, the water tank is filled with water and the water temperature is set at 40°C. The water heater heats the water and keeps the temperature at 40°C. On the other hand, the fuel is inserted into the small part of the viscometer until the 75 ml mark. Thereafter, the viscometer is located in the water tank which is stable at 40°C. The viscosity adjustment tools used in the fuel viscosity experiment are given in Figure 2.35.

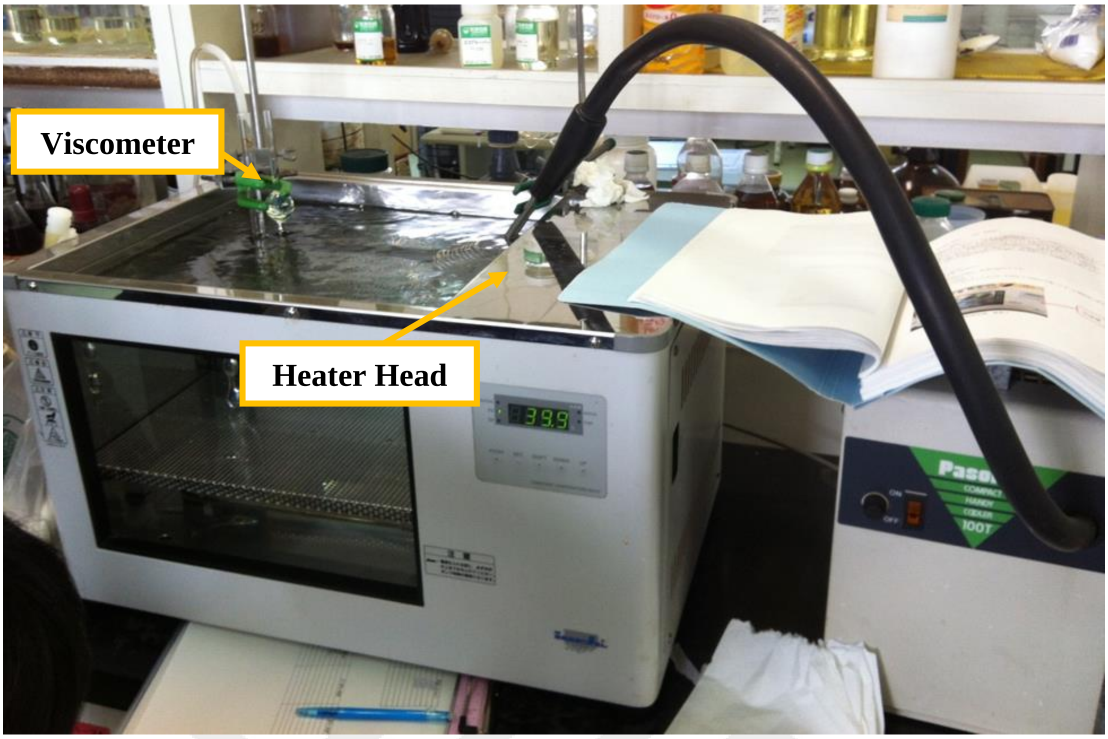


Figure 2.35. Fuel viscosity adjustment tools

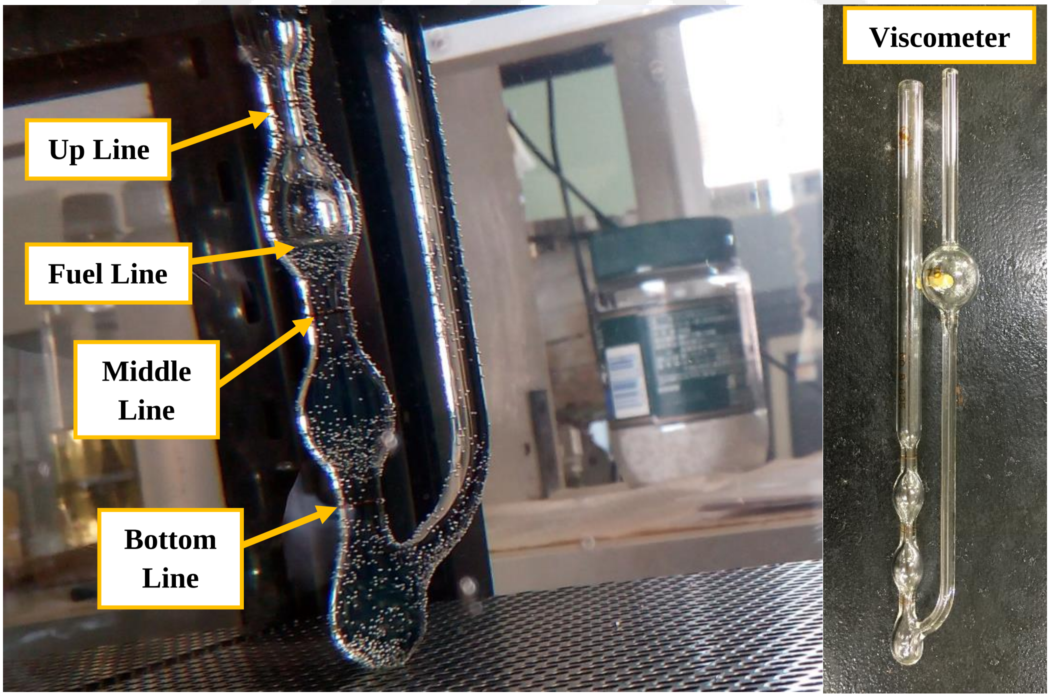


Figure 2.35. Fuel viscosity adjustment tools (Continued)

Over time, the fuel rises in the viscometer. Firstly, it rises from bottom line to middle line, then from middle line to up line. These times are counted and the viscosity of the fuel is calculated considering this time. When the experiment is done, the viscometer is then washed with acetone to clean the viscometer from the previous fuel and then the experiment can start again with a different fuel. The viscometer cleaner devise is shown in Figure 2.36.

Figure 2.36. Viscometer cleaner

2.5.2.2. Oil Viscosity

The viscosity adjustment tools in the oil viscosity experiment are shown in Figure 2.37. First, engine oil is added to the glass beaker up to m_3. Then, the beaker filled with this engine oil is placed in a glass container filled with fuel. The oil is put on the heater. The heater temperature is set to 90°C and the fuel temperature is expected to reach 90°C. The mixer is used to make this temperature rising process easier. This mixer helps to heat up by mixing the fuel. On the other hand, engine oil is expected to reach m_2 level. The time from level m_3 to level m_2 is checked. This time is used in the viscosity calculation formula, so that the viscosity of the oil is calculated.

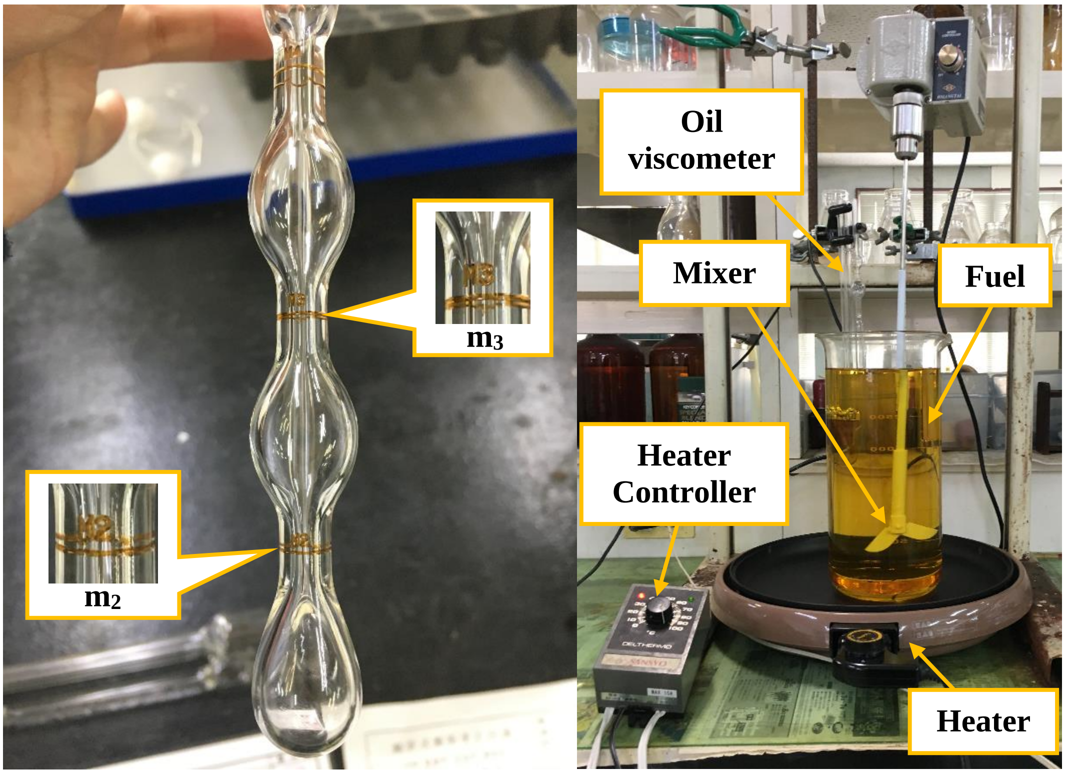


Figure 2.37. Oil viscosity adjustment tools

2.5.3. Acid Number

The acid value (or "neutralization number" or "acid number" or "acidity") is the mass of potassium hydroxide (KOH) in milligrams that is required to neutralize one gram of chemical substance. The number of acids is a measure of the amount of a mixture of carboxylic acid groups or compounds in a chemical compound such as a fatty acid. According to a typical procedure, a known amount of sample dissolved in an organic solvent (mostly isopropanol) is titrated with a potassium hydroxide (KOH) solution with a known concentration and phenolphthalein is used as a color indicator [54].

The acid number is used to quantify the amount of acid present in a sample of fuel (e.g. biodiesel). This is the amount of base expressed in milligrams of potassium hydroxide required to neutralize the acidic components in the 1 g sample. The experimental process of the number of acid of the fuel can be explained as follows:

(i) First, 500 ml of toluene, 495 ml of 2-propanol and 5 ml of water are mixed. 50 ml of this mixture, 20 g of fuel, 8 drops of Phenolphthalein, 1 ml of hydrochloric acid (HCl) is transferred into the beaker glass and the mixture is removed by means of a magnetic stirrer.

(ii) Then, 250 ml of 2-Propanol and 1.64 g of Potassium Hydroxide (KOH) are mixed and the mixture is taken up in the buret. Subsequently, this mixture is sent to the other compound in the beaker. The new mixture in the cup becomes orange in color.

(iii) Finally, titration is done to determine how much KOH is needed to neutralize the fuel. As a result, the acid number of the fuel is known. This process is performed on all fuels using similar methods. Some of the chemicals used in the acid sample test are given in Figure 2.39; some tools and titration process of the acid number experiment are shown in Figure 2.40.

Figure 2.38. Some chemicals used in the acid number experiment

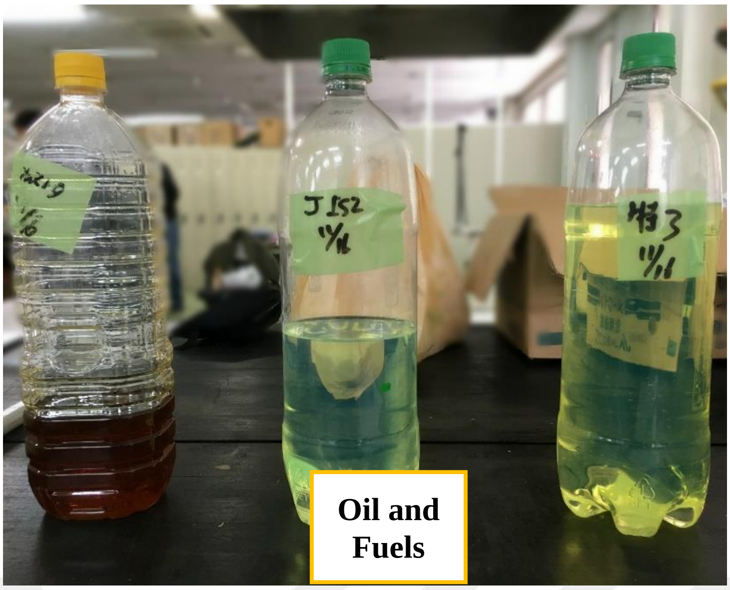


Figure 2.38. Some chemicals used in the acid number experiment (Continued)

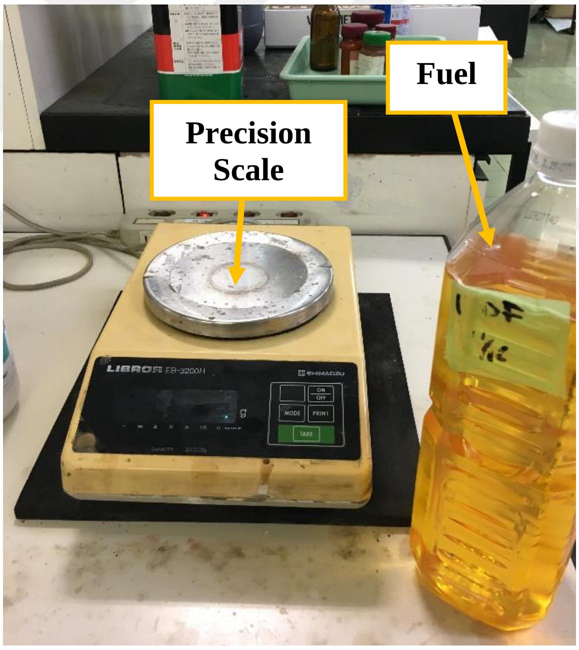


Figure 2.39. Precision scale and fuel for the titration process of the acid number experiment

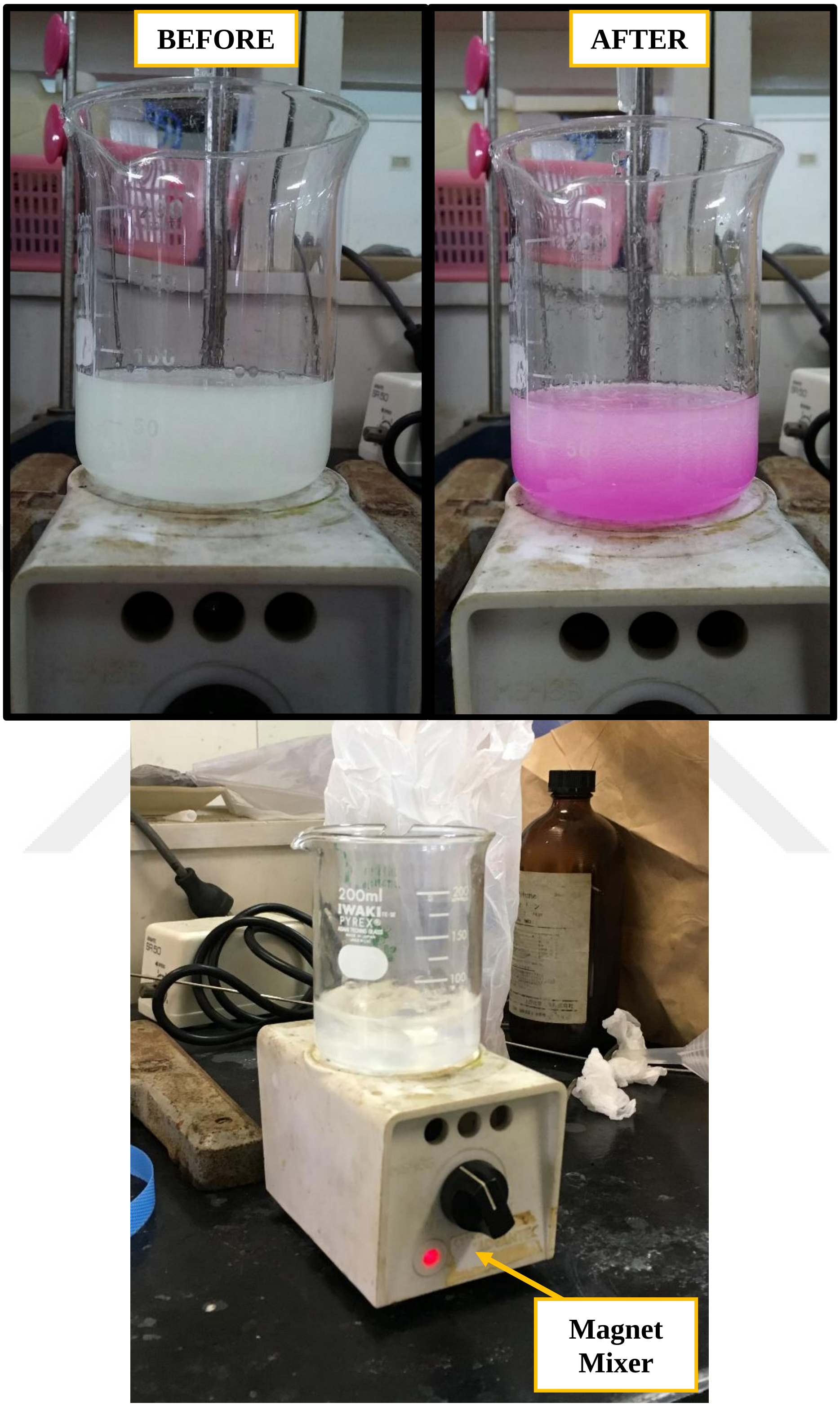


Figure 2.40. Some tools and titration process of the acid number experiment

2.5.4. Flash Point

The flash point is a descriptive characteristic that is used to distinguish flammable liquids (such as petrol) from combustible liquids. It is also used to characterize liquid fire hazards. Depending on the standard that is used, liquids which have a flash point less than either 37.8°C or 60.5°C are called flammable, whereas liquids having a flash point above that temperature are called combustible. Every liquid has a vapor pressure, which is a function of that liquid's temperature. As the temperature increases, the vapor pressure increases. As the vapor pressure increases, the concentration of vapor of the flammable liquid in the air increases. Hence, temperature determines the concentration of vapor of the flammable liquid in the air. A certain concentration of vapor in the air is necessary to sustain combustion, and that concentration is different for each flammable liquid. The flash point of a flammable liquid is the lowest temperature at which there will be enough flammable vapor to ignite when an ignition source is applied [55].

In the flash point test, the container is first filled with fuel and opened to heat the fuel. Then, the flowing LPG (Liquid Petroleum Gas) is opened and the fuse is lifted up. The fuel temperature is increased until it is high enough. Then, the plate is opened to fire the fuel. If the fuel gets on fire, the fuel has reached its flash point. If the fuel does not get on fire, it is checked again when the temperature is high. When the experiment is finished, the fuel container is drained and washed for starting the experiment again with different fuels. The flash point experiment device is shown in Figure 2.41.

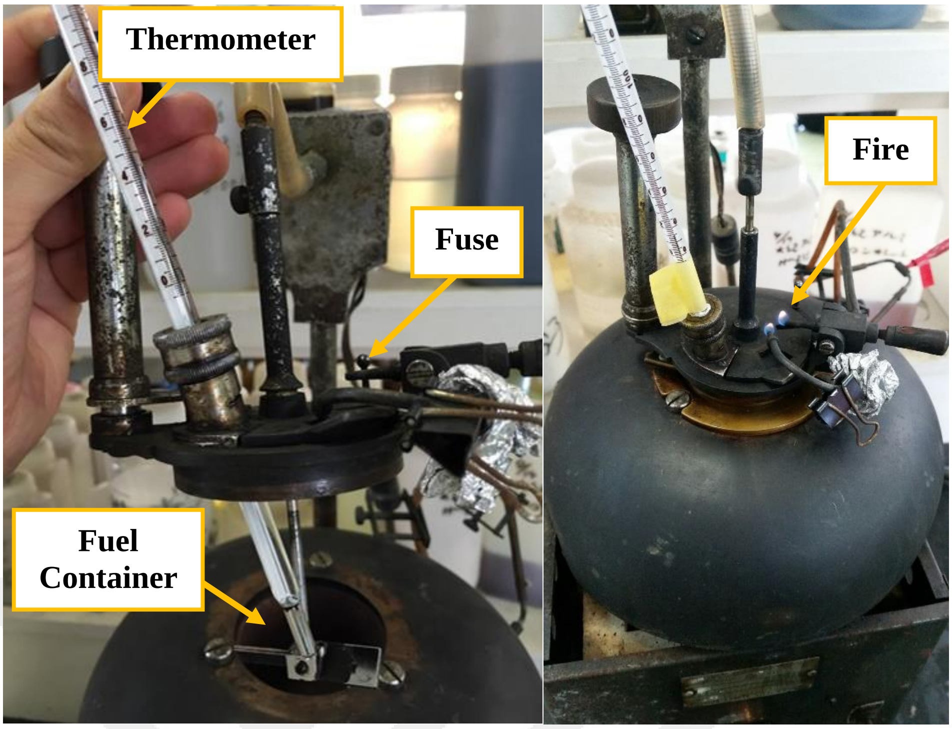


Figure 2.41. Flash point experiment device

2.5.5. Cloud Point & Pour Point

Cloud point and pour point are important physical properties of any liquid fuel. Cloud point is the temperature at which a cloud of wax crystals first appears in a liquid fuel (crystals of solid biodiesel) when it is cooled under special testing conditions. Pour point is just the opposite of cloud point as it refers to the lowest temperature at which movement of oil is observed and the fuel can be pumped easily. As such there is only a slight difference in these two temperatures on the temperature scale but the difference between cloud point and pour point is significant in the use of any fuel.

Cloud point is taken as the temperature below which wax in fuel tends to form a cloudy appearance. This is a condition which is detrimental for any engine as solidified wax makes the fuel thick and it clogs the fuel filters and injectors. This wax also gets applied on the pipeline and has a tendency to form an emulsion with water. This is a property that holds great significance in cold weathers. Cloud point is also referred to as wax appearance temperature.

In addition, pour point is the lowest temperature at which the fuel continues to flow. Pour point of a fuel is an indication of the temperature at which fuel can still be pumped.

Alternately, pour point can also be described as the lowest temperature at which a fuel performs satisfactorily and beyond this temperature, the fuel stops flowing and starts to freeze [56]. The cloud point and pour point experiment device is illustrated in Figure 2.42.

Figure 2.42. Cloud point and pour point experiment device

As a result of the experiments in the laboratory, the measurement results are taken directly from the measurement screen. The measured data of the system in the engine test laboratory is given in Table 2.5.

Table 2.5. Measured data of the system in the engine test laboratory mean values

Engine Load	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
		10^{-3}						10^{-3}	10^{-6}			
Engine Out												
Biodiesel												
100 Nm	98.26	1.415	32.793	24.90	27.44	80.00	294.20	27.993	3.5285	0.3268	16.3697	4452.0832
200 Nm	196.33	2.492	53.133	25.36	44.52	80.00	321.00	57.319	2.9572	0.2487	42.4895	7852.5503
294 Nm	266.15	3.312	63.981	25.60	53.64	80.02	364.80	66.650	2.2695	0.2281	86.4713	10432.3911
Diesel												
100 Nm	102.58	1.358	31.495	24.68	26.32	80.02	304.40	29.859	4.0221	0.5181	14.9786	4268.7132
200 Nm	197.90	2.329	49.692	25.28	41.58	80.00	332.40	57.319	3.8075	0.6666	36.1040	7326.0414
294 Nm	284.39	3.210	61.047	25.48	51.12	80.08	392.80	70.382	3.2590	0.8087	80.4834	10098.1106
DOC only												
Biodiesel												
100 Nm	98.46	1.410	32.932	25.96	27.51	80.00	288.80	19.462	0.0307	0.0557	7.7553	4467.6271
200 Nm	196.92	2.561	55.005	26.22	45.98	80.08	313.20	57.319	0.0511	0.0771	22.0068	8119.8090
Diesel												
100 Nm	100.62	1.386	32.523	25.58	27.08	80.00	297.20	19.995	0.0303	0.0675	6.0280	4386.9564
200 Nm	199.66	2.380	51.089	26.26	42.61	80.08	326.40	43.189	0.0474	0.0901	16.0969	7529.6018
DPF only												
SiC only												
Biodiesel												
100 Nm	98.46	1.393	32.730	26.90	27.93	80.06	291.40	21.061	3.6714	0.2697	16.2574	4413.7590
200 Nm	196.13	2.487	53.109	27.46	45.38	80.02	318.60	44.949	3.0537	0.2074	42.9251	7888.6982
Diesel												
100 Nm	97.87	1.365	32.104	26.38	26.86	80.02	297.60	23.194	3.7089	0.4867	15.0354	4312.1433
200 Nm	197.50	2.354	50.554	26.76	42.35	80.02	327.80	47.988	3.5944	0.5684	38.3749	7445.3370
Cordierite only												
Biodiesel												
100 Nm	97.09	1.428	33.421	26.48	28.39	80.00	290.00	22.661	3.7924	0.2575	17.1344	4519.8357
200 Nm	194.76	2.550	54.552	27.00	46.42	80.06	317.20	47.668	3.1454	0.1932	45.2945	8083.6115
Diesel												
100 Nm	98.65	1.365	32.048	25.52	26.82	80.02	297.20	21.5946	3.7555	0.4645	16.2857	4323.3760
200 Nm	196.92	2.351	50.652	26.00	42.42	80.02	326.80	45.322	3.6478	0.5604	38.6874	7452.6580

Table 2.5. Measured data of the system in the engine test laboratory mean values (Continued)

Engine Load	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
		10^{-3}						10^{-3}	10^{-6}			
DOC+DPF												
DOC+SiC												
Biodiesel												
100 Nm	98.26	1.439	32.730	26.32	28.15	80.00	292.60	26.660	0.0314	0.0585	5.2415	4561.0324
200 Nm	197.11	2.526	53.109	26.46	45.25	80.02	318.80	56.786	0.0502	0.0706	17.5832	8013.4929
Diesel												
100 Nm	100.52	1.370	32.104	25.54	26.83	80.00	301.00	27.726	0.0296	0.0543	5.3677	4343.4606
200 Nm	198.09	2.369	50.554	25.76	42.62	80.04	333.20	57.052	0.0469	0.0812	14.5012	7515.5798
DOC+Cordierite												
Biodiesel												
100 Nm	100.52	1.435	33.421	27.44	28.46	80.02	294.00	26.660	0.0312	0.0487	5.3975	4564.1409
200 Nm	196.33	2.525	54.552	27.58	45.98	80.02	320.60	54.653	0.0502	0.0601	17.4302	8030.6851
Diesel												
100 Nm	101.20	1.388	32.048	25.32	27.07	80.00	300.40	25.594	0.0302	0.0469	4.4568	4409.0229
200 Nm	197.70	2.396	50.652	25.86	43.00	80.08	329.80	53.320	0.0478	0.0653	13.0848	7601.2302

3. ANALYSIS

Thermodynamic analyses are applied to the system. According to thermodynamic analyses; the energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic and exergoeconomic analyses are exerted to the system data. The control volume of the engine is given in Figure 3.1.

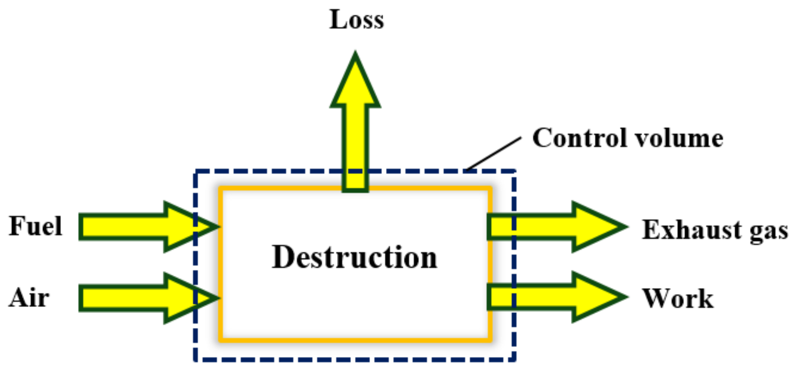


Figure 3.1. Control volume of the engine

3.1. Energy Analysis

Energy analysis is related to the first law of thermodynamics in terms of energy balance and energy efficiency. In addition, energy analysis is the method of evaluating the energy used in an operation involving the physical or chemical processing of materials and the transfer or conversion of energy. The energy balance of the system is given as follows [28]:

$$\sum \dot{E}n_{in} = \sum \dot{E}n_{out} \tag{1}$$

$$\dot{E}n_{air} + \dot{E}n_{fuel} = \dot{E}n_{W} + \dot{E}n_{exh} + \dot{E}n_{loss} \tag{2}$$

where $\sum \dot{E}n_{in}$ is the total energy input rate and $\sum \dot{E}n_{out}$ is the total energy output rate of the system. In addition, $\dot{E}n_{air}$ is the energy rate of air, $\dot{E}n_{fuel}$ is the energy rate of fuel, $\dot{E}n_{W}$ is the work rate, $\dot{E}n_{exh}$ is the exhaust energy rate, and $\dot{E}n_{loss}$ is the energy loss rate of the system.

The energy rate of air ($\dot{E}n_{air}$) can be found by

$$\dot{E}n_{air} = \dot{m}_{air} h_{air} = \rho_{air} \dot{V}_{air} h_{air} \tag{3}$$

where $\dot{m}_{air}$ is the mass flow rate of air, $\dot{V}_{air}$ is the volumetric flow rate of air, ρ_{air} is the density of air (around 1.17 g/L) and h_{air} is the enthalpy of the air [24].

The energy rate of fuel ($\dot{E}n_{fuel}$) is defined from

$$\dot{E}n_{fuel} = \dot{m}_{fuel} H_u \tag{4}$$

where $\dot{m}_{fuel}$ is the mass flow rate of fuel and H_u is the Lower Heating Value (LHV) of fuel.

The low heating value of the fuel (H_u) can be calculated as follows:

$$H_u = \frac{H_{u,density} + H_{u,viscosity}}{2} \tag{5}$$

where $H_{u,density}$ and $H_{u,viscosity}$ are the lower heating values of the fuel (in kJ/kg) found from the density of fuel (ρ_{fuel}) and kinematic viscosity of fuel (μ_{fuel}), respectively [28].

$$H_{u,density} = [(-0.167)\rho_{fuel} + 184.95]10^3 \tag{6}$$

$$H_{u,viscosity} = [(-12.88)\ln(\mu_{fuel}) + 61.3]10^3 \tag{7}$$

The work rate of the system ($\dot{E}n_W$) can be calculated from

$$\dot{E}n_W = \omega \mathrm{T} \tag{8}$$

where ω is the angular velocity and T is the torque of the engine.

The angular velocity of the engine is calculated by

$$\omega = \frac{2\pi n}{60} \tag{9}$$

where n is the speed of the engine in revolutions per minute (1800 rpm).

The exhaust energy rate of the system ($\dot{E}n_{exh}$) is determined as follows:

$$\dot{E}n_{exh} = \dot{m}_{CO}h_{CO} + \dot{m}_{NO_x}h_{NO_x} + \dot{m}_{CO_2}h_{CO_2} + \dot{m}_{HC}h_{HC} \tag{10}$$

where, $\dot{m}$ is the mass flow rate and h is the enthalpy of the exhaust gas component. Calculation of mass flow rates and enthalpies of exhaust gases (CO, NO_x, CO_2 and HC) is required.

The energy loss rate of the system ($\dot{E}n_{loss}$) can be found from the energy balance equation as follows:

$$\dot{E}n_{loss} = \dot{E}n_{air} + \dot{E}n_{fuel} - \dot{E}n_{W} - \dot{E}n_{exh} \tag{11}$$

The energy efficiency of the system (η) is calculated by

$$\eta = \left(\frac{\dot{E}n_{W}}{\dot{E}n_{fuel}} \right) 100 \tag{12}$$

3.2. Exergy Analysis

The energy analysis method alone is not enough to understand all aspects of the energy systems. It also does not quantify the usefulness or quality of the various energy flows that flow through a system. Thus, the method of exergy analysis based on the first and second laws of thermodynamics is used to understand real thermodynamic behaviour of the system. Exergy is also defined as potential or quality of energy. With exergy analysis, a sustainable quality assessment of the energy systems can be done. Moreover, the main purposes of the exergy analysis are to determine the actual efficiency and true magnitudes of exergy losses and destruction. The exergy destruction mentioned here is proportional to entropy formation. In the actual process, some exergy is destroyed due to the second law of thermodynamics.

In addition, the reference environment is important for exergy analysis. When a thermodynamic system is in balance with the environment, the state of the system is called as "dead state", and the temperature of this case is called to be "dead state temperature" (or reference temperature). Also, the pressure in this state is called as “dead state pressure” [57].

Exergy balance of the system is written follows:

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \dot{E}x_{dest} \tag{13}$$

$$\dot{E}x_{air} + \dot{E}x_{fuel} = \dot{E}x_{W} + \dot{E}x_{exh} + \dot{E}x_{loss} + \dot{E}x_{dest} \tag{14}$$

where $\sum \dot{E}x_{in}$ is the total exergy input rate, $\sum \dot{E}x_{out}$ is total exergy output rate and $\dot{E}x_{dest}$ is exergy destruction rate of the system. In addition, $\dot{E}x_{air}$, $\dot{E}x_{fuel}$, $\dot{E}x_{W}$, $\dot{E}x_{exh}$ and $\dot{E}x_{loss}$ are the exergy rate of air, exergy rate of fuel, exergetic work rate, exhaust exergy rate and exergy loss rate of the system, respectively.

The exergy rate of air ($\dot{E}x_{air}$) is found from

$$\dot{E}x_{air} = \dot{m}_{air}\, c_{p,air,in}\left[\left(T_{air,in} - T_0\right) - T_0 \ln\left(\frac{T_{air,in}}{T_0}\right)\right] \tag{15}$$

where $c_{p,air,in}$ is the specific heat capacity of intake air, $T_{air,in}$ is the inlet temperature of the intake air, and T_0 is the dead state (reference) temperature (21°C).

The exergy rate of fuel ($\dot{E}x_{fuel}$) can be determined by [29]

$$\dot{E}x_{fuel} = \dot{m}_{fuel}\, H_u\, \varepsilon_{fuel} \tag{16}$$

where ε_{fuel} is the chemical exergy factor of fuel as follows [58]:

$$\varepsilon_{fuel} = (1.0401) + (0.1728)\frac{H}{C} + (0.0432)\frac{O}{C} + (0.2169)\frac{\alpha}{C}\left[1 - (2.0628)\frac{H}{C}\right] \quad (17)$$

where *H*, *O*, *C*, α are the mass ratios of Hydrogen, Oxygen, Carbon and Sulphur of fuel, respectively. In addition, the ε_{fuel} value can be taken between 1.04 and 1.08 for diesel and biodiesel fuels [58]. The ε_{fuel} value of biodiesel is 1.0751 and the ε_{fuel} value of the diesel fuel is 1.0697 [25].

The exergetic work rate ($\dot{E}x_W$) is equal to the energetic work rate:

$$\dot{E}x_W = \dot{E}n_W \quad (18)$$

The exhaust exergy of the system ($\dot{E}x_{exh}$) is found as follows:

$$\dot{E}x_{exh} = \sum_{i=1}^{n} \dot{m}_i \left(ex_{tm,i} + ex_{ch,i}\right) \quad (19)$$

where $ex_{tm,i}$ and $ex_{ch,i}$ the specific thermomechanical (physical) and specific chemical exergy rates of the *i*th exhaust gas component, respectively. For each exhaust gases (HC, CO, CO_2, NO_x, etc.), these parameters are found.

The specific thermomechanical (physical) exergy rate of the *i*th exhaust gas component ($ex_{tm,i}$) is found from

$$ex_{tm,i} = \left[(h_i - h_0) - T_0(s_i - s_0)\right] = c_{p,i}\left[(T_{exh} - T_0) - T_0 \ln\left(\frac{T_{exh}}{T_0}\right)\right] \quad (20)$$

where T_{exh} is the exhaust temperature of the engine.

The specific chemical exergy rate of the of the *i*th exhaust gas component ($ex_{ch,i}$) is determined from

$$ex_{ch,i} = \bar{R}\, T_0 \ln\left(\frac{y_i}{y_{env,i}}\right) \tag{21}$$

In this formula, $\bar{R}$ is the universal gas constant (8.314 kJ/kmolK), y_i is the molar fraction of *i*th exhaust gas component in the exhaust gases, and $y_{env,i}$ is the molar fraction of *i*th exhaust gas component in the environment. Therefore, the $ex_{ch,i}$ value is calculated in kJ/kmol. Thus, the molar weight of the *i*th exhaust gas component is necessary to change the unit in kJ/kg [29]. The molar fractions of the exhaust gas components in the exhaust gases and environment are given in Table 3.1 through Table 3.7. Furthermore, thermodynamic parameters used in the analyses are tabulated in Table 3.8, while the specific heat capacities of the air and exhaust gases are given in Table 3.9.

Table 3.1. Molar fractions of the exhaust gas components for measured values of without after treatment system

Molar fractions of exhaust gas components in the exhaust gases "y_i" (%)				
Fuel	Exhaust gas	100 Nm	200 Nm	294 Nm
Biodiesel	CO	0.0116	0.0060	0.0039
	HC	0.0022	0.0010	0.0008
	NO_x	0.0328	0.0527	0.0895
	CO_2	9.3580	10.2240	11.3440
Diesel	CO	0.0138	0.0083	0.0058
	HC	0.0036	0.0029	0.0029
	NO_x	0.0314	0.0482	0.0880
	CO_2	9.3500	10.2100	11.5280

Table 3.2. Molar fractions of the exhaust gas components for measured values of DOC only

Molar fractions of exhaust gas components in the exhaust gases " y_i " (%)			
Fuel	Exhaust gas	100 Nm	200 Nm
Biodiesel	CO	0.0001	0.0001
	HC	0.0004	0.0003
	NO_x	0.0148	0.0252
	CO_2	9.2960	10.1520
Diesel	CO	0.0001	0.0001
	HC	0.0005	0.0004
	NO_x	0.0117	0.0200
	CO_2	9.2560	10.1560

Table 3.3. Molar fractions of the exhaust gas components for measured values of SiC DPF only

Molar fractions of exhaust gas components in the exhaust gases " y_i " (%)			
Fuel	Exhaust gas	100 Nm	200 Nm
Biodiesel	CO	0.0120	0.0062
	HC	0.0018	0.0008
	NO_x	0.0310	0.0505
	CO_2	9.2260	10.2060
Diesel	CO	0.0124	0.0077
	HC	0.0033	0.0024
	NO_x	0.0300	0.0487
	CO_2	9.2180	10.1440

Table 3.4. Molar fractions of the exhaust gas components for measured values of cordierite DPF only

Molar fractions of exhaust gas components in the exhaust gases " y_i " (%)			
Fuel	Exhaust gas	100 Nm	200 Nm
Biodiesel	CO	0.0122	0.0062
	HC	0.0017	0.0008
	NO_x	0.0320	0.0520
	CO_2	9.2660	10.1880
Diesel	CO	0.0125	0.0077
	HC	0.0031	0.0024
	NO_x	0.0318	0.0480
	CO_2	9.2300	10.1100

Table 3.5. Molar fractions of the exhaust gas components for measured values of DOC+SiC

Molar fractions of exhaust gas components in the exhaust gases " y_i " (%)			
Fuel	Exhaust gas	100 Nm	200 Nm
Biodiesel	CO	0.0001	0.0001
	HC	0.0004	0.0003
	NO_x	0.0098	0.0205
	CO_2	9.2960	10.2000
Diesel	CO	0.0001	0.0001
	HC	0.0004	0.0004
	NO_x	0.0106	0.0181
	CO_2	9.3680	10.2460

Table 3.6. Molar fractions of the exhaust gas components for measured values of DOC+Cordierite

Molar fractions of exhaust gas components in the exhaust gases " y_i " (%)			
Fuel	Exhaust gas	100 Nm	200 Nm
Biodiesel	CO	0.0001	0.0001
	HC	0.0003	0.0002
	NO_x	0.0099	0.0199
	CO_2	9.3580	10.2280
Diesel	CO	0.0001	0.0001
	HC	0.0003	0.0003
	NO_x	0.0086	0.0160
	CO_2	9.3240	10.1700

Table 3.7. Molar fractions of the exhaust gas components in the environment [33]

Molar fractions of the exhaust gas components in the environment " $y_{env,i}$ " (%)	
N_2	75.6700
O_2	20.3500
CO_2	0.03450
H_2O	3.03000
CO	0.00070
SO_2	0.00020
H_2	0.00005
Others	0.91455

The exergy loss rate of the system ($\dot{E}x_{loss}$) is determined as follows:

$$\dot{E}x_{loss} = \dot{E}n_{loss}\left(1-\frac{T_0}{T_{cw}}\right) \tag{22}$$

where T_{cw} is the cooling water temperature of the engine.

The exergy destruction rate of the system ($\dot{E}x_{dest}$) can be found from the exergy balance equation as follows:

$$\dot{E}x_{dest} = \dot{E}x_{air} + \dot{E}x_{fuel} - \dot{E}x_{W} - \dot{E}x_{exh} - \dot{E}x_{loss} \tag{23}$$

The exergy efficiency of the system (ψ) is calculated from

$$\psi = \left(\frac{\dot{E}x_{W}}{\dot{E}x_{fuel}}\right)100 \tag{24}$$

The entropy generation rate (S_{gen}) is determined from

$$S_{gen} = \frac{\dot{E}x_{dest}}{T_0} \tag{25}$$

Table 3.8. Thermodynamic parameters used in the analyses [59,60]

	Enthalpy (*h*) (kJ/kg)					Entropy (*s*) (kJ/kgK)				
	Air	CO	HC	NO_x	CO_2	Air	CO	HC	NO_x	CO_2
Engine Out										
Biodiesel										
100 Nm	396.2988	618.0013	-	-	471.1407	2.7501	9.3673	-	-	6.1414
200 Nm	396.7608	646.9961	-	-	499.6648	2.7517	9.2045	-	-	6.0551
294 Nm	397.0020	694.7783	-	-	547.1430	2.7525	9.2373	-	-	6.1037
Diesel										
100 Nm	396.0778	628.6261	-	-	481.5656	2.7494	9.3674	-	-	6.1481
200 Nm	396.6804	659.3856	-	-	511.9213	2.7514	9.2252	-	-	6.0755
294 Nm	396.8814	725.5832	-	-	578.0227	2.7521	9.2685	-	-	6.1408
DOC only										
Biodiesel										
100 Nm	397.3637	612.1806	-	-	465.4439	2.7506	9.4649	-	-	6.2000
200 Nm	397.6249	638.5385	-	-	491.3206	2.7515	9.2723	-	-	6.0933
Diesel										
100 Nm	396.9819	621.2380	-	-	474.3130	2.7492	9.4728	-	-	6.2105
200 Nm	397.6651	652.8606	-	-	505.4615	2.7515	9.2984	-	-	6.1183
DPF only										
SiC only										
Biodiesel										
100 Nm	398.3082	614.9823	-	-	468.1846	2.7585	9.4464	-	-	6.1899
200 Nm	398.3082	644.3921	-	-	497.0937	2.7585	9.2733	-	-	6.0974
Diesel										
100 Nm	397.7857	621.6697	-	-	474.7364	2.7526	9.4296	-	-	6.1833
200 Nm	398.1675	654.3823	-	-	506.9670	2.7539	9.2696	-	-	6.1009
Cordierite only										
Biodiesel										
100 Nm	397.8862	613.4735	-	-	466.7083	2.7566	9.4220	-	-	6.1735
200 Nm	398.4087	642.8737	-	-	495.5954	2.7583	9.2520	-	-	6.0829
Diesel										
100 Nm	396.9216	621.2380	-	-	474.3130	2.7497	9.4501	-	-	6.1960
200 Nm	397.4039	653.2953	-	-	505.8915	2.7513	9.2848	-	-	6.1099

Table 3.8. Thermodynamic parameters used in the analyses (Continued) [59,60]

	Enthalpy (*h*) (kJ/kg)					Entropy (*s*) (kJ/kgK)				
	Air	CO	HC	NO_x	CO_2	Air	CO	HC	NO_x	CO_2
DOC+DPF										
DOC+SiC										
Biodiesel										
100 Nm	397.7254	616.2759	-	-	469.4509	2.7521	9.3787	-	-	6.1476
200 Nm	397.8661	644.6090	-	-	497.3078	2.7526	9.2032	-	-	6.0529
Diesel										
100 Nm	396.9417	625.3411	-	-	478.3389	2.7526	9.3830	-	-	6.1558
200 Nm	397.1627	660.2563	-	-	512.7841	2.7533	9.2280	-	-	6.0779
DOC+Cordierite										
Biodiesel										
100 Nm	398.8508	617.7856	-	-	470.9294	2.7595	9.3814	-	-	6.1502
200 Nm	398.9914	646.5620	-	-	499.2361	2.7600	9.2179	-	-	6.0634
Diesel										
100 Nm	396.7206	624.6930	-	-	477.7026	2.7490	9.4057	-	-	6.1698
200 Nm	397.2632	656.5570	-	-	509.1196	2.7508	9.2420	-	-	6.0846

Table 3.9. Specific heat capacities of the air and exhaust gases [59,60]

Specific heat capacity (c_p) (kJ/kgK)					
	Air	CO	HC	NO_x	CO_2
Engine Out					
Biodiesel					
100 Nm	1.00418	1.07855	-	1.08381	1.05656
200 Nm	1.00476	1.08532	-	1.09855	1.07196
294 Nm	1.00476	1.09653	-	1.12140	1.09569
Diesel					
100 Nm	1.00409	1.08107	-	1.08942	1.06252
200 Nm	1.00476	1.08825	-	1.10482	1.07830
294 Nm	1.00476	1.10384	-	1.13540	1.10987
DOC only					
Biodiesel					
100 Nm	1.00477	1.07725	-	1.08084	1.05335
200 Nm	1.00478	1.08330	-	1.09426	1.06757
Diesel					
100 Nm	1.00476	1.07929	-	1.08546	1.05833
200 Nm	1.00478	1.08674	-	1.10152	1.07496

Table 3.9. Specific heat capacities of the air and exhaust gases (Continued) [59,60]

Specific heat capacity (c_p) (kJ/kgK)					
	Air	CO	HC	NO_x	CO_2
DPF only					
SiC only					
Biodiesel					
100 Nm	1.00480	1.07787	-	1.08227	6.18991
200 Nm	1.00480	1.08469	-	1.09723	1.07062
Diesel					
100 Nm	1.00479	1.07939	-	1.08568	1.05856
200 Nm	1.00480	1.08709	-	1.10229	1.07573
Cordierite only					
Biodiesel					
100 Nm	1.00479	1.07754	-	1.08150	1.05407
200 Nm	1.00480	1.08433	-	1.09646	1.06983
Diesel					
100 Nm	1.00476	1.07929	-	1.08546	1.05833
200 Nm	1.00478	1.08684	-	1.10174	1.07518
DOC+DPF					
DOC+SiC					
Biodiesel					
100 Nm	1.00478	1.07816	-	1.08293	1.05561
200 Nm	1.00479	1.08474	-	1.09734	1.07073
Diesel					
100 Nm	1.00476	1.08023	-	1.08755	1.06055
200 Nm	1.00477	1.08845	-	1.10526	1.21232
DOC+Cordierite					
Biodiesel					
100 Nm	1.00482	1.07850	-	1.08370	1.05644
200 Nm	1.00482	1.08521	-	1.09833	1.07174
Diesel					
100 Nm	1.00476	1.08008	-	1.08722	1.06020
200 Nm	1.00477	1.08760	-	1.10339	1.07685

3.3. Sustainability Analysis

Sustainable development requires efficient use of resources and the exergy method is necessary to increase productivity and maximizes the benefits of resources for societies, while minimizing adverse effects. More efficiency allows to contribute to the development of resources for a longer period of time. Sustainability analysis is associated with the Sustainability Index (*SI*) parameter as a function of the exergy efficiency. There is no unit for the SI parameter. Sustainability index is used to compare the systems. So, it can be applicable for the parametric studies or the variable data assessment.

The *SI* method based on exergy efficiency is a useful tool for achieving the sustainability of the system as follows [57]:

$$SI = \frac{1}{1-\psi} \tag{26}$$

3.4. Environmental Analysis

The use of energy resources causes environmental problems. Carbon dioxide (CO_2) has great influence on environmental causes. As a result of the burning of the fuels, the CO2 emissions are separated from the engine exhaust. In addition, all of the fuels cause different CO_2 emissions depending on their different chemical properties.

When the CO_2 emissions of fuels and the work rate generated by the system are taken into consideration, the environmental analysis can be written as follows [61]:

$$x_{CO_2} = y_{CO_2} \dot{E}n_W \Delta t_{working} \tag{27}$$

where x_{CO_2} is the CO_2 emission releasing in a day (kg-CO_2/day), y_{CO_2} is the CO_2 emission value of the fuel (kg-CO_2/kWh), $\dot{E}n_W$ is the generated work rate of the engine (kW) and $\Delta t_{working}$ is the working hours of the engine in a day (8 h/day).

Table 3.10. Measured CO_2 emission values of the fuels

y_{CO_2} (kg-CO_2/kWh)		
Engine Out		
	Biodiesel	Diesel
100 Nm	0.8658	0.7948
200Nm	0.7641	0.7069
294 Nm	0.7487	0.6781
DOC only		
100 Nm	0.8664	0.8326
200Nm	0.7873	0.7199
DPF only		
SiC only		
100 Nm	0.8565	0.8414
200 Nm	0.7680	0.7198
Cordierite only		
100 Nm	0.8888	0.8373
200 Nm	0.7924	0.7228
DOC+DPF		
DOC+SiC		
100 Nm	0.8565	0.8414
200 Nm	0.7680	0.7198
DOC+Cordierite		
100 Nm	0.8868	0.8244
200 Nm	0.7760	0.7245

3.5. Enviroeconomic Analysis

The enviroeconomic analysis can also be called as environmental cost analysis. In this analysis, the carbon emission price per day and the amount of carbon emissions emitted by the system are used. Determination of the carbon price has an important role in reducing harmful emissions. Atmospheric carbon emissions (CO_2) can be priced to reduce CO_2 emissions releasing. Carbon prices can be assumed between 0.013 \$/kg-CO_2 and 0.016 \$/kg-CO_2 [28].

The exergoeconomic method is determined with CO_2 emission and its cost as follows [61]:

$$C_{CO_2} = c_{CO_2}\ x_{CO_2} \tag{28}$$

where C_{CO_2} ($/day), c_{CO_2} (0.0145 $/kg-CO2) and x_{CO_2} (kg-CO2/day) are the enviroeconomic parameters, CO_2 emission price per kg-CO_2 and CO_2 emission releasing in a day, respectively [28].

3.6. Thermoeconomic Analysis

Thermoeconomic analysis can be applied according to the thermoeconomic parameter that provides the link between energy loss and capital cost [57]:

$$R_{en} = \frac{\dot{E}n_{loss}}{K} \tag{29}$$

where $\dot{E}n_{loss}$ is the energy loss rate (kW), K is the capital cost of the system and R_{en} is the thermoeconomic parameter (kW/$). It is assumed that capital cost of the diesel engine unit is 200,000 $. Thanks to the thermoeconomic parameter, the information about losses per capital cost of the system can be obtained.

3.7. Exergoeconomic Analysis

Exergoeconomic analysis is an exergy-based economic analysis method in which costs are better distributed among outputs. There are different methods of exergoeconomic analysis. In this study, the EXergy-Cost-Energy-Mass (EXCEM) approach is used. For the exergoeconomic analysis, the relations between capital costs, exergy losses and exergy destructions are considered as follows [57]:

$$R_{ex} = R_{ex,loss} + R_{ex,dest} \tag{30}$$

$$R_{ex,loss} = \frac{\dot{E}x_{loss}}{K} \tag{31}$$

$$R_{ex,dest} = \frac{\dot{E}x_{dest}}{K} \tag{32}$$

where $R_{ex,loss}$ is the exergoeconomic parameter for loss and $R_{ex,dest}$ is the exergoeconomic parameter for destruction. In addition, $\dot{E}x_{loss}$, $\dot{E}x_{dest}$ and R_{ex} are the exergy loss rate (kW), exergy destruction rate (kW) and total exergoeconomic parameter (kW/$), respectively.

3.8. Error Analysis

The numerical values, obtained as a result of the measurements, are only meaningful when given together with measurement errors. Physical measurements are not error-free. To better express this ambiguity, an error analysis needs to be performed to ensure that the data are obtained in the best possible way [62].

An expression that indicates how much each of the discrete x_i(i = 1, ..., k) measurements differs from the average value ($\bar{x}$) is called "deviation". ith deviation for the measurement can be found as [62]:

$$a_i = x_i - \bar{x} \tag{33}$$

where the a_i values can be positive, negative or zero. If the a_i values are all very small, then our measurements are so close together.

The measurement results can be evaluated more precisely with an absolute definition which is known as "standard deviation". Standard deviation (σ) can be calculated from [62]

$$\sigma = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{k}(a_i)^2} = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{k}(x_i - \bar{x})^2} \tag{34}$$

where n is the total number of experimental tests. This expression also can be explained as the mean square root of the squares of the deviations in the measurements x_1, ..., x_k.

Besides the standard deviation, additional calculation is necessary for better and precisely evaluation of the measurement data. This calculation is called "relative error". Relative error can be obtained from [62]

$$Relative\ error = \frac{|x_g - \bar{x}|}{x_g} \tag{35}$$

where x_g is the real value of the measurement/test result. Relative error is often called "fractional error", so, it is generally given in percentage.

4. RESULTS AND DISCUSSION

4.1. Measurement/Test Results

The biodiesel and diesel fuels are used in the diesel engine at 100 Nm, 200 Nm and 294 Nm for without after treatment system test, while they are tested at 100 Nm and 200 Nm engine loads for various after treatment systems (DOC and DPFs). While the EGR is off, the exhaust emissions, specific fuel consumptions, particle concentration and soot of the engine are experimentally analyzed. Also, the energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic and exergoeconomic analyses are applied to the system.

The mean values of the measurement/test results for without after treatment is given in Table 4.1. In all variations of system (for without after treatment and after treatment systems); as engine load increases, NO_x emissions increase for both fuels. The NO_x emission value is directly proportional to the engine torque. While NO_x emissions are minimum at 100 Nm load and maximum at 294 Nm for the without after treatment system, it is minimum at 100 Nm load and maximum at 200 Nm for the after treatment systems. However, CO, HC and CO_2 emissions are inversely proportional to engine load, relative to all fuel types used in the engine.

When after treatment systems are not used, the minimum CO and HC emission rates are usually found for the biodiesel fuel, while the maximum ones are determined for the diesel fuel. Moreover, the maximum NO_x and CO_2 emissions rates are usually obtained for the biodiesel fuel and the minimum ones are found for the diesel fuel.

In this study, the biodiesel fuel contains more oxygen and less carbon molecules than the diesel fuel. Thus, when the biodiesel fuel is burned, CO_2 and NO_x emissions occur higher than diesel fuel. On the other hand, the situation is exactly the opposite for the CO and HC emissions. Because, diesel fuels contain more carbon and less oxygen molecules than biodiesel fuels [25]. The maximum CO_2 emission is calculated as 865.7768 g/kWh for the biodiesel fuel, while the minimum one is calculated as 678.0731 g/kWh for the diesel fuel for the without after treatment system. Also, the maximum NO_x emission is found as 6.2058 g/kWh for the biodiesel fuel, while the minimum one is calculated as 2.7889 g/kWh for the diesel fuel. On the other hand, the minimum CO and HC emissions are found at 294 Nm as 0.1629 g/kWh and 0.0164 g/kWh for the biodiesel fuel, while the maximum CO and HC emissions are found at 100 Nm engine load as 0.7489 g/kWh and 0.0965 g/kWh for the diesel fuel. Mean values of measurement/test results without after treatment can be seen in Table 4.1. In addition, the exhaust emissions of the fuels at 100 Nm, 200 Nm and 294 Nm for without after treatment system can be seen in Figure 4.1, while the comparison of the exhaust emissions of the fuels at 294 Nm for without after treatment system are given in Figure 4.2.

Table 4.1. Mean values of the measurement/test results for without after treatment

	Total Particle Concentration (#/cm³)	Soot (mg/m³)	Fuel Consumption (g/kWh)	Exhaust Emission (g/kWh)				Lower Heating Value (kJ/kg)
				CO	HC	NO_x	CO_2	
Biodiesel								
100 Nm	3674650.84	0.880	275.09	0.6862	0.0635	3.1833	865.7768	37655.88
200 Nm	1784501.04	0.384	242.54	0.2878	0.0242	4.1347	764.1286	
294 Nm	916323.69	0.270	237.71	0.1629	0.0164	6.2058	748.7056	
Diesel								
100 Nm	6134041.20	2.158	252.84	0.7489	0.0965	2.7889	794.7880	45236.42
200 Nm	3885427.84	1.538	224.69	0.3674	0.0643	3.4834	706.8507	
294 Nm	2205061.04	1.234	215.55	0.2188	0.0543	5.4043	678.0731	

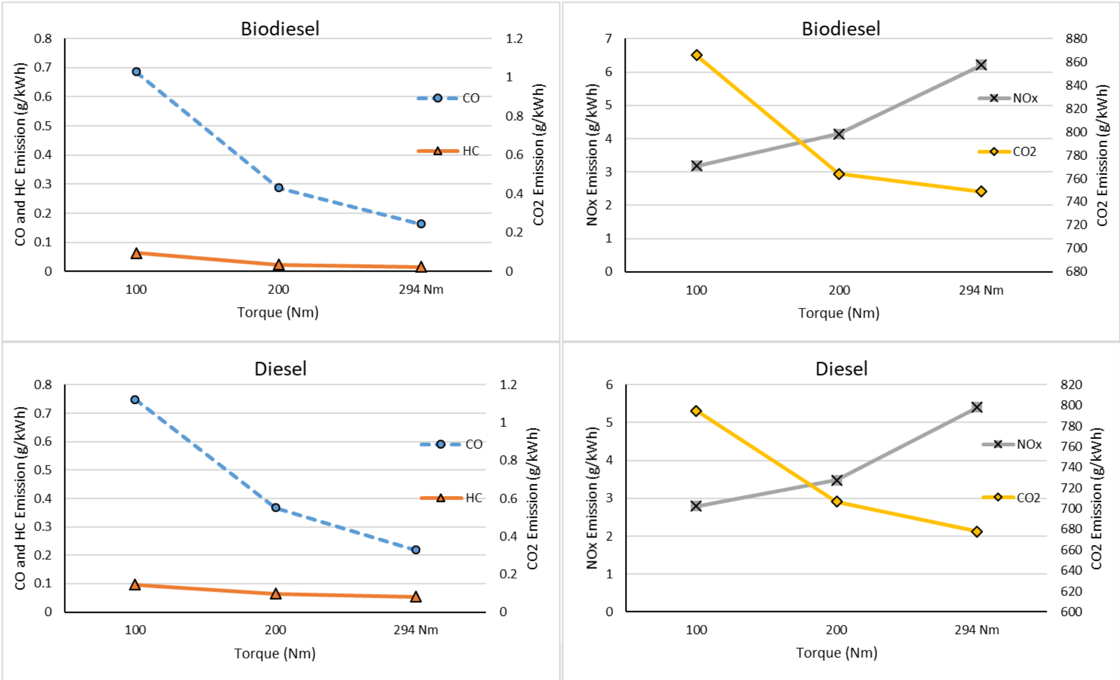


Figure 4.1. Exhaust emissions of the fuels at 100 Nm, 200 Nm and 294 Nm for without after treatment system

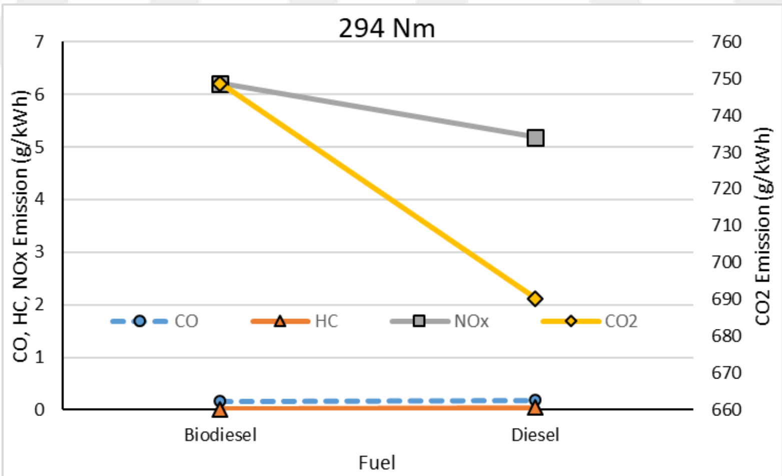


Figure 4.2. Comparison of the exhaust emissions in terms of fuels at 294 Nm for without after treatment system

The Lover Heating Values (LHVs) of the fuels are found as 37655.88 kJ/kg and 45236.42 kJ/kg for the biodiesel and diesel fuels, respectively. The LHVs of the fuels do not change for the with and without after treatment tests. The maximum specific fuel consumption is found as 275.09 g/kWh at 100 Nm torque, and the minimum specific fuel consumption is calculated as 215.55 g/kWh at 294 Nm for the diesel fuel. The Lower Heating Values (LHVs) of the fuels are given in Figure 4.3 and the specific fuel consumptions of the system for without after treatment can be seen in Figure 4.4.

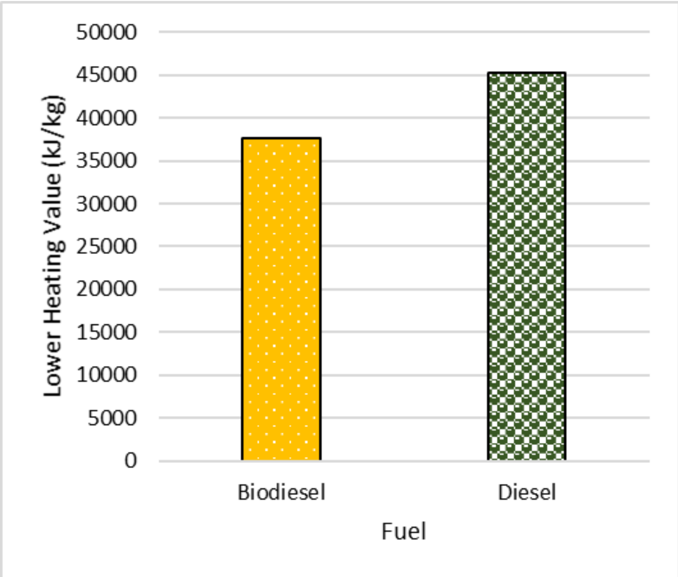


Figure 4.3. Lower Heating Values (LHVs) of the fuels

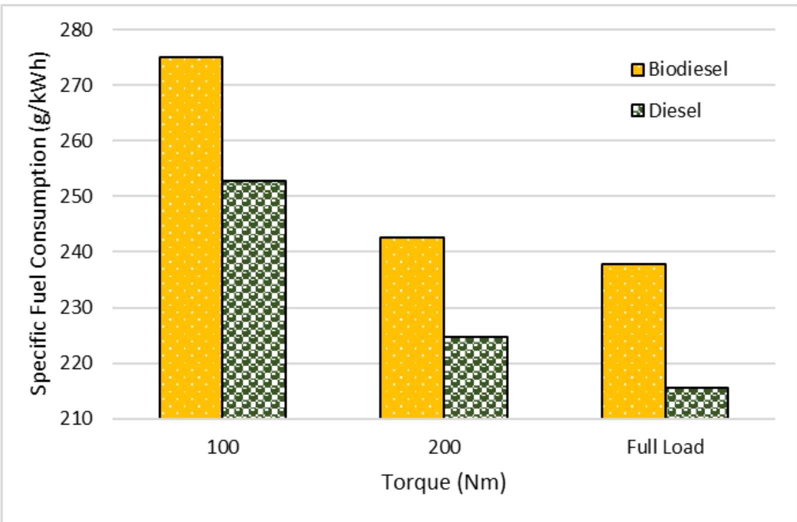


Figure 4.4. Specific fuel consumptions of the system for without after treatment

For the after treatment system, the maximum CO and HC emissions rates are found different than the without after treatment system. When DOC after treatment is used alone, the maximum CO emission rate is calculated as 0.0060 g/kWh at 100 Nm torque for the biodiesel fuel, and the maximum HC emission rate is calculated as 0.0128 g/kWh at 200 Nm torque for the diesel fuel, while the minimum HC emission rate is calculated as 0.0075 g/kWh at 200 Nm torque for the biodiesel fuel and the minimum CO emission rate is found as 0.0045 g/kWh at 200 Nm torque for the diesel fuel. Moreover, the maximum NO_x and CO_2 emissions rates are usually determined for the biodiesel fuel as 2.1337 g/kWh and 866.4374 g/kWh, respectively; while the minimum ones are obtained for the diesel fuel as 1.1442 g/kWh and 719.9255 g/kWh, respectively. In addition, the maximum specific fuel consumption is calculated as 273.36 g/kWh at 100 Nm torque for the biodiesel fuel, and the minimum one is determined as 227.52 g/kWh at 200 Nm torque for the diesel fuel. The mean values of measurement/test results for DOC only can be seen in Table 4.2, while the exhaust emissions of the fuels at 100 Nm and 200 Nm for DOC only are shown in Figure 4.5. Also, the specific fuel consumptions of the system for DOC only are illustrated in Figure 4.6.

Table 4.2. Mean values of the measurement/test results for DOC only

	Total Particle Concentration (#/cm³)	Soot (mg/m³)	Fuel Consumption (g/kWh)	Exhaust Emission (g/kWh)				Lower Heating Value (kJ/kg)
				CO	HC	NO_x	CO_2	
Biodiesel								
100 Nm	3355338.84	0.890	273.36	0.0060	0.0108	1.5038	866.4374	37655.88
200 Nm	1520881.04	0.342	248.31	0.0050	0.0075	2.1337	787.2896	
Diesel								
100 Nm	5126050.16	1.932	263.11	0.0058	0.0128	1.1442	832.5812	45236.42
200 Nm	3219749.12	1.458	227.52	0.0045	0.0086	1.5391	719.9255	

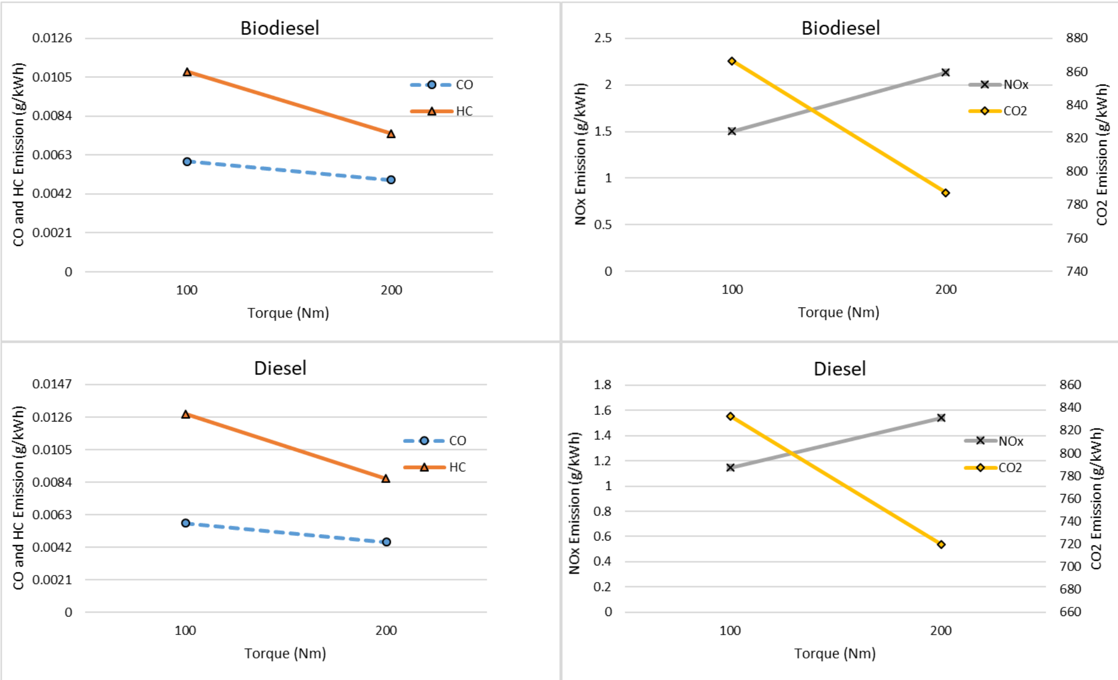


Figure 4.5. Exhaust emissions of the fuels at 100 Nm and 200 Nm for DOC only

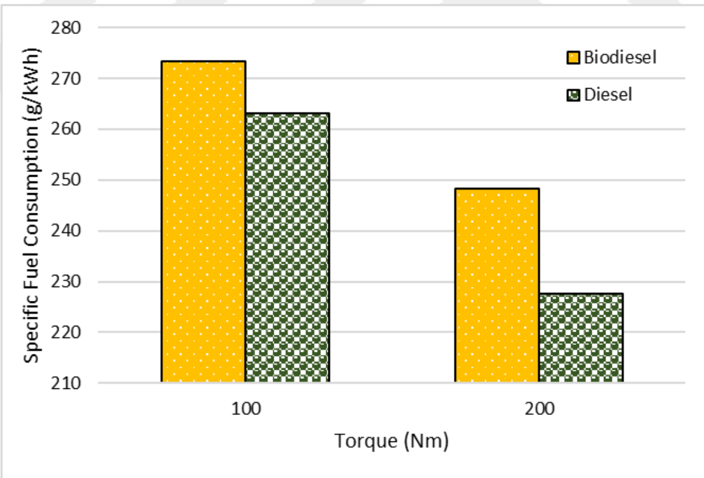


Figure 4.6. Specific fuel consumptions of the system for DOC only

When SiC DPF after treatment system is used alone, the minimum CO and HC emissions rates are found as 0.2973 g/kWh and 0.0202 g/kWh at 200 Nm torque for the biodiesel fuel, respectively; the maximum CO and HC emissions rates are also calculated as 0.7237 g/kWh and 0.0949 g/kWh for the diesel fuel at 100 Nm torque. Furthermore, the maximum NO_x emission rate is determined as 4.1789 g/kWh at 200 Nm torque for the biodiesel fuel, while the minimum one is obtained as 2.9337 g/kWh at 200 Nm torque for the diesel fuel. In addition, the maximum CO_2 emission is found as 856.5364 g/kWh at 100 Nm torque for the biodiesel fuel, while the minimum one is calculated as 719.7948 g/kWh at 200 Nm torque for the diesel fuel. Also, the maximum specific fuel consumption is determined as 270.27 g/kWh for the biodiesel fuel at 100 Nm engine load, and the minimum one is found as 227.61 g/kWh for the diesel fuel at 200 Nm engine load. The mean values of measurement/test results for SiC only can be seen in Table 4.3, while the exhaust emissions of the fuels at 100 Nm and 200 Nm for SiC only are shown in Figure 4.7. In addition, the specific fuel consumptions of the system for SiC only are illustrated in Figure 4.8.

Table 4.3. Mean values of the measurement/test results for SiC only

	Total Particle Concentration (#/cm³)	Soot (mg/m³)	Fuel Consumption (g/kWh)	Exhaust Emission (g/kWh)				Lower Heating Value (kJ/kg)
				CO	HC	NO_x	CO_2	
Biodiesel								
100 Nm	531.73	0.054	270.27	0.7130	0.0524	3.1539	856.5364	37655.88
200 Nm	352.45	0.048	242.13	0.2973	0.0202	4.1789	768.0479	
Diesel								
100 Nm	544.45	0.014	266.40	0.7237	0.0949	2.9337	841.3523	45236.42
200 Nm	602.99	0.008	227.61	0.3475	0.0550	3.7100	719.7948	

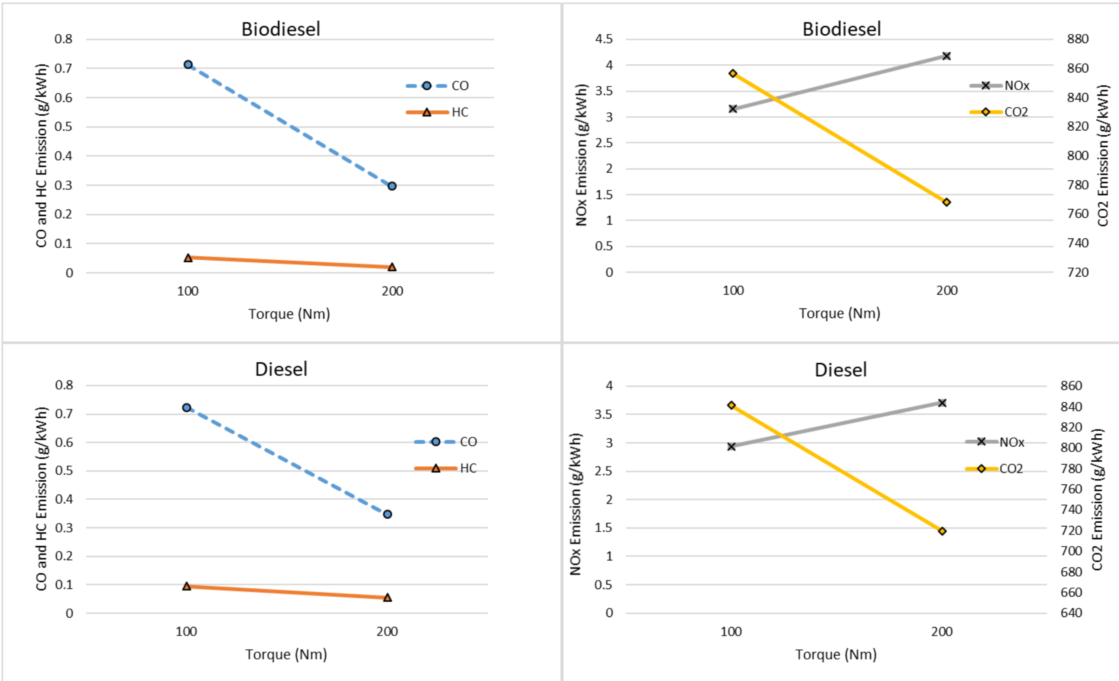


Figure 4.7. Exhaust emissions of the fuels at 100 Nm and 200 Nm for SiC only

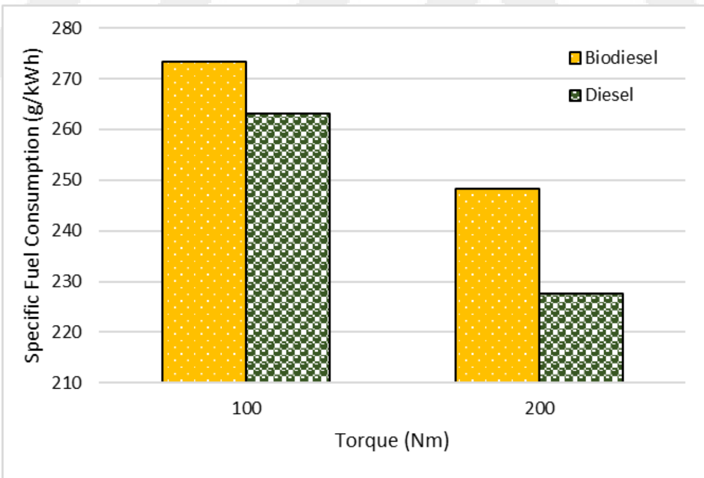


Figure 4.8. Specific fuel consumptions of the system for SiC only

If cordierite DPF after treatment system is used alone, the CO emissions change depending on the engine loads. The CO emission of the biodiesel fuel is more than the diesel fuel's CO emission at 100 Nm. However, this situation is exactly the opposite at 200 Nm. The maximum CO emission rate is calculated as 0.7458 g/kWh at 100 Nm torque, while the minimum one is found as 0.3083 g/kWh at 200 Nm torque for the biodiesel fuel. In addition, the minimum HC emission rate is found as 0.0189 g/kWh at 200 Nm engine load for the biodiesel fuel and the maximum HC emission rate is calculated as 0.09 g/kWh at 100 Nm engine load for the diesel fuel. Moreover, the maximum NO_x and CO_2 emissions rates are found for the biodiesel fuel as 4.4398 g/kWh at 200 Nm torque and 888.8440 g/kWh at 100 Nm torque, respectively; while the minimum ones are determined for the diesel fuel as 3.3695 g/kWh at 100 Nm torque and 722.8249 g/kWh at 200 Nm torque. Also, the minimum specific fuel consumption is found as 228.06 g/kWh at 200 Nm engine load for the diesel fuel, while the maximum one is determined as 707.84 g/kWh at 100 Nm engine load for the biodiesel fuel. The mean values of measurement/test results for cordierite only can be seen in Table 4.4, while the exhaust emissions of the fuels at 100 Nm and 200 Nm for cordierite only are shown in Figure 4.9. In addition, the specific fuel consumptions of the system for cordierite only are illustrated in Figure 4.10.

Table 4.4. Mean values of the measurement/test results for cordierite only

	Total Particle Concentration (#/cm³)	Soot (mg/m³)	Fuel Consumption (g/kWh)	Exhaust Emission (g/kWh)				Lower Heating Value (kJ/kg)
				CO	HC	NO_x	CO_2	
Biodiesel								
100 Nm	340.53	0.036	280.84	0.7458	0.0506	3.3695	888.8440	37655.88
200 Nm	571.47	0.026	249.98	0.3083	0.0189	4.4398	792.3839	
Diesel								
100 Nm	707.84	0.014	264.27	0.7273	0.0900	3.1540	837.2769	45236.42
200 Nm	584.37	0.030	228.06	0.3538	0.0543	3.7522	722.8249	

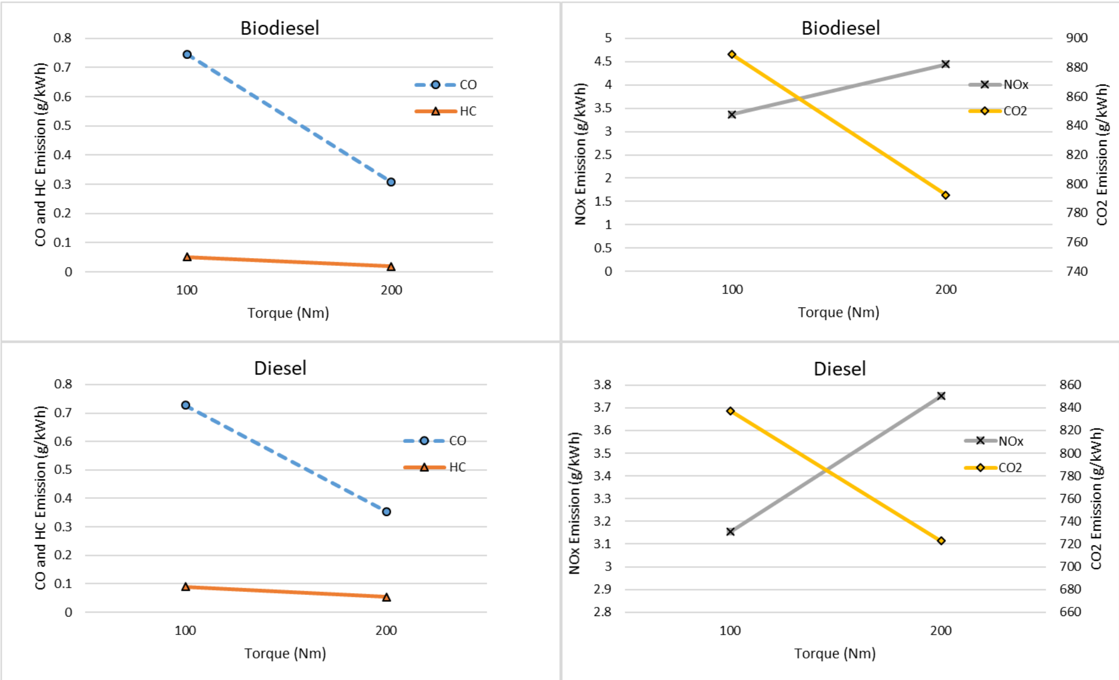


Figure 4.9. Exhaust emissions of the fuels at 100 Nm and 200 Nm for cordierite only

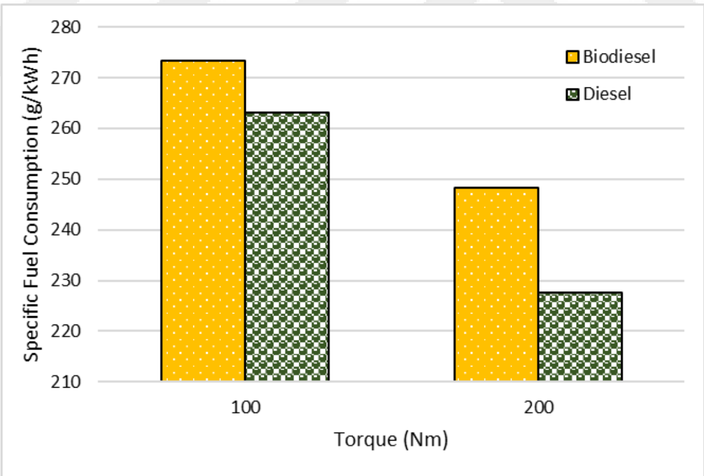


Figure 4.10. Specific fuel consumptions of the system for cordierite only

When DOC and SiC DPF after treatment systems are used together, the maximum CO emission rate is found as 0.0061 g/kWh at 100 Nm torque for the biodiesel fuel, while the minimum CO emission rate is calculated as 0.0045 g/kWh at 200 Nm torque for the diesel fuel. On the other hand, the HC emissions depend on the engine load. The maximum HC emission rate is determined as 0.0114 g/kWh at 100 Nm torque, while the minimum HC emission rate is found as 0.0068 g/kWh at 200 Nm torque for the biodiesel fuel. It is also founded that the maximum NO_x and CO_2 emissions rates are determined as 1.7027 g/kWh at 200 Nm engine load and 886.8030 g/kWh at 100 Nm engine load for the biodiesel fuel, respectively. The minimum ones are obtained as 1.0188 g/kWh at 100 Nm engine load and 724.4645 g/kWh at 200 Nm engine load for the diesel fuel. In addition, the maximum specific fuel consumption is found as 279.68 g/kWh at 100 Nm torque for the biodiesel fuel, while the minimum one is determined as 0.030 g/kWh at 200 Nm torque for the diesel fuel. The mean values of measurement/test results for DOC+SiC can be seen in Table 4.5, while the exhaust emissions of the fuels at 100 Nm and 200 Nm for DOC+SiC are shown in Figure 4.11. In addition, the specific fuel consumptions of the system for DOC+SiC are illustrated in Figure 4.12.

Table 4.5. Mean values of the measurement/test results for DOC+SiC

	Total Particle Concentration (#/cm³)	Soot (mg/m^3)	Fuel Consumption (g/kWh)	Exhaust Emission (g/kWh)				Lower Heating Value (kJ/kg)
				CO	HC	NO_x	CO_2	
Biodiesel								
100 Nm	1062.57	0.036	279.68	0.0061	0.0114	1.0194	886.8030	37655.88
200 Nm	527.14	0.034	244.63	0.0049	0.0068	1.7027	776.0298	
Diesel								
100 Nm	2312.68	0.085	259.98	0.0056	0.0103	1.0188	824.4327	45236.42
200 Nm	1132.38	0.030	228.41	0.0045	0.0078	1.3979	724.4645	

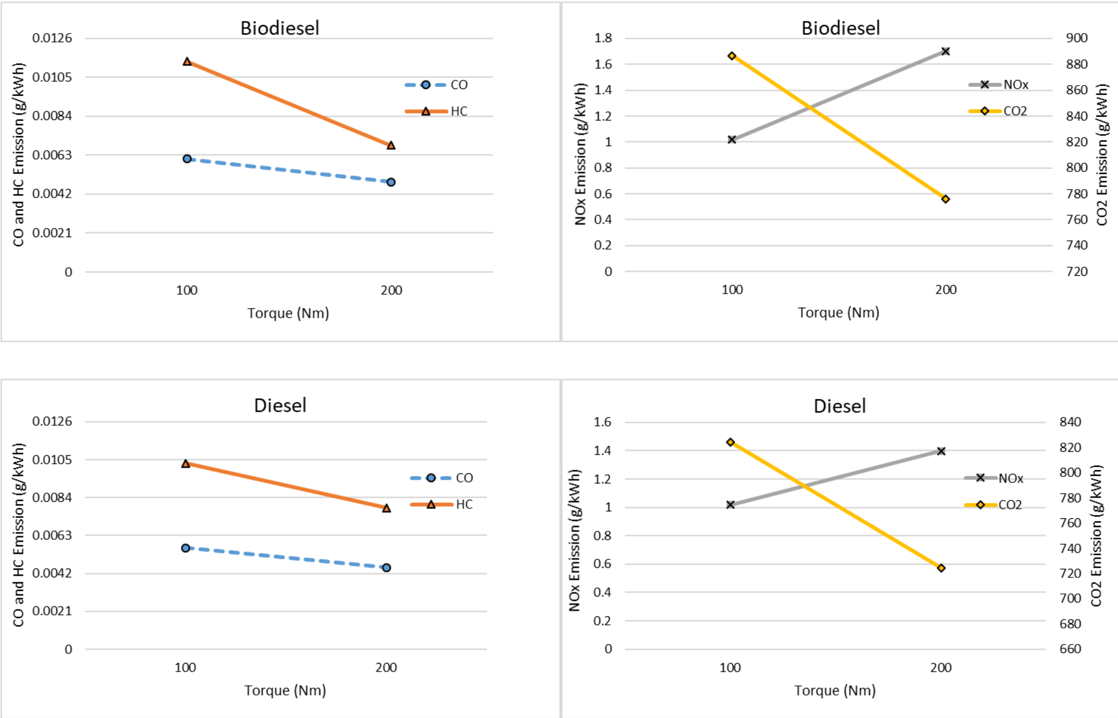


Figure 4.11. Exhaust emissions of the fuels at 100 Nm and 200 Nm for DOC+SiC

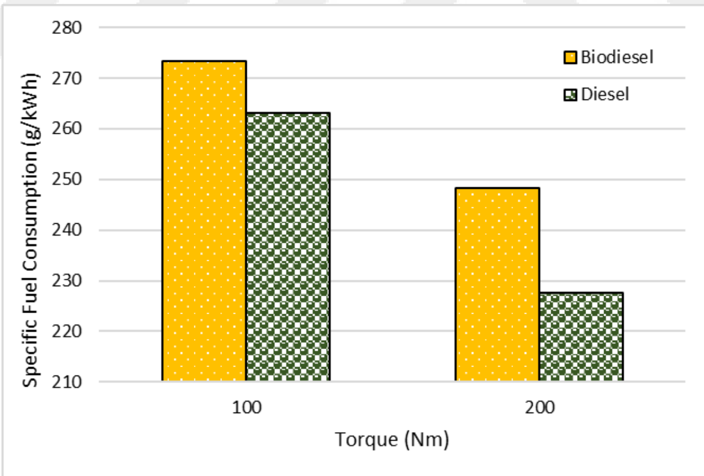


Figure 4.12. Specific fuel consumptions of the system for DOC+SiC

If DOC and cordierite DPF after treatment systems are used together, the maximum CO and HC emissions rates are calculated as 0.0059 g/kWh and 0.0093 g/kWh at 100 Nm torque for the biodiesel fuel, respectively. In this regard, the minimum CO emission rate is found as 0.0046 g/kWh at 200 Nm torque for the biodiesel fuel and minimum THC emission rate is found as 0.0058 for the diesel fuel. However, the maximum NO_x emission rate is determined as 1.6954 g/kWh at 200 Nm engine load and the maximum CO_2 emission rate is determined as 866.5233 g/kWh at 100 Nm engine load for the biodiesel fuel, while the minimum ones are obtained as 0.8409 g/kWh for NO_x emission rate and 733.7645 g/kWh for CO_2 emission rate for the diesel fuel at 100 Nm and 200 Nm engine load, respectively. In addition, the minimum specific fuel consumption is found as 231.25 g/kWh at 200 Nm torque for the diesel fuel and the maximum one is determined as 272.47 g/kWh at 100 Nm torque for the biodiesel fuel. The mean values of measurement/test results for DOC+Cordierite can be seen in Table 4.6 and the exhaust emissions of the fuels at 100 Nm and 200 Nm for DOC+Cordierite are shown in Figure 4.13. In addition, the specific fuel consumptions of the system for DOC+Cordierite are illustrated in Figure 4.14.

Table 4.6. Mean values of the measurement/test results for DOC+Cordierite

	Total Particle Concentration (#/cm³)	Soot (mg/m³)	Fuel Consumption (g/kWh)	Exhaust Emission (g/kWh)				Lower Heating Value (kJ/kg)
				CO	HC	NO_x	CO_2	
Biodiesel								
100 Nm	29083.44	0.060	272.47	0.0059	0.0093	1.0249	866.5233	37655.88
200 Nm	25143.79	0.038	245.57	0.0049	0.0058	1.6954	781.0647	
Diesel								
100 Nm	106564.11	0.078	261.82	0.0057	0.0089	0.8409	831.8262	45236.42
200 Nm	39097.55	0.026	231.25	0.0046	0.0063	1.2631	733.7645	

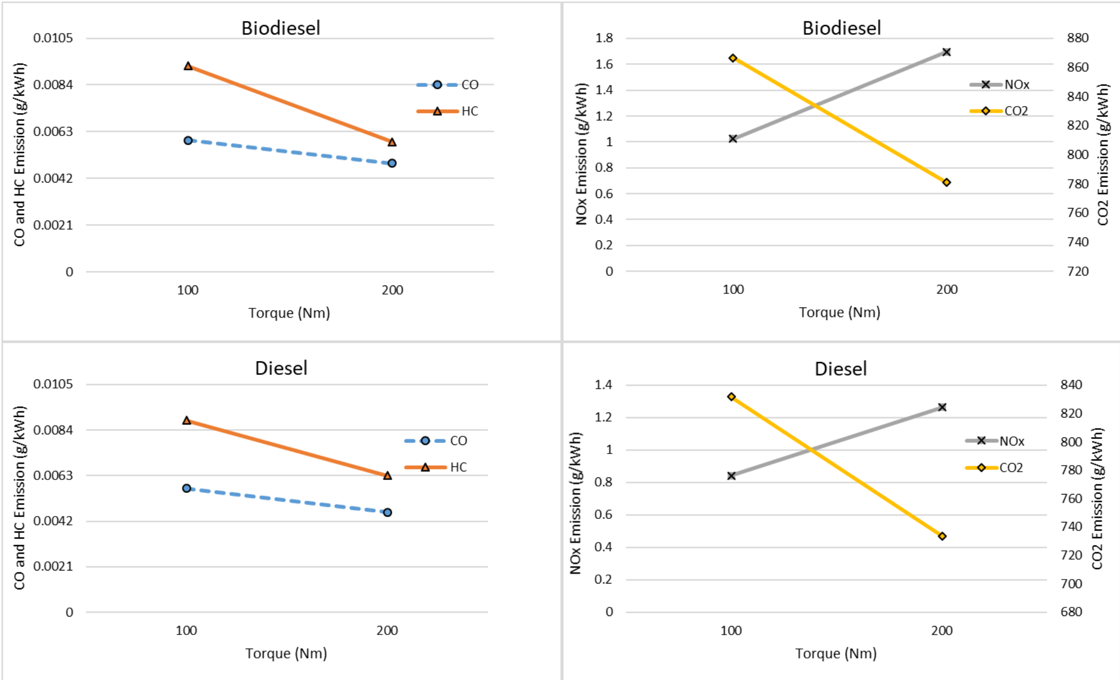


Figure 4.13. Exhaust emissions of the fuels at 100 Nm and 200 Nm for DOC+Cordierite

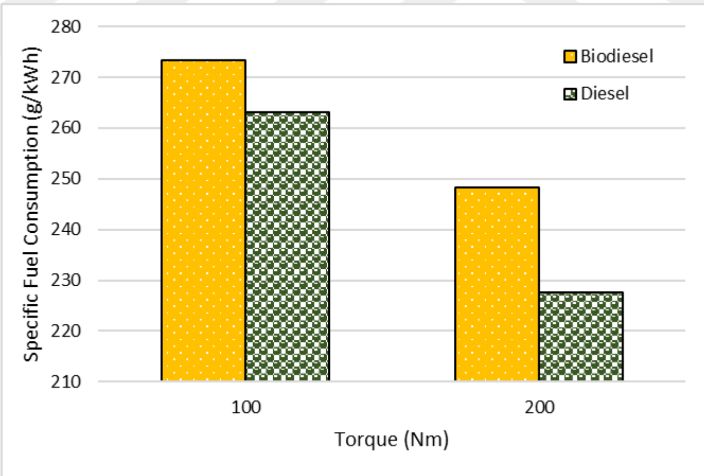


Figure 4.14. Specific fuel consumptions of the system for DOC+Cordierite

The particle concentration varies in particle mobility diameters. Indeed, the particle concentration values change at various engine loads such as 100 Nm, 200 Nm and 294 Nm. The reason for this change is that the full burning of the fuels takes place. Therefore, the number of particles varies depending on the engine load. However, it can be clearly seen that the biodiesel fuel has minimum particle concentration, while the diesel fuel has the maximum particle concentration. Both of the fuels have more total particle concentrations at 100 Nm. If the engine load is 200 Nm and 294 Nm, the total particulate concentrations of the fuels reduce. Therefore, this means that the particle concentrations of the fuels are inversely proportional to the engine load. This shows the same result for with and without after treatment systems. In this regard, the maximum 'total' particle concentration is found as 6134041.20 1/cm^3 at 100 Nm engine load for the diesel fuel, while the minimum one is determined as 916323.69 1/cm^3 at 294 Nm for the biodiesel fuel for the without after treatment system. So, biodiesel fuels are better options than diesel fuels. Because, the particle concentration should be minimum for better environment. In addition, engine load is also an important influence on the environment. For a better environment, the engines can be operated at higher loads. The variation of particle concentration of fuels at 100 Nm, 200 Nm and 294 Nm for without after treatment system is shown in Figure 4.15. In addition, the comparison of the total particle concentration changes of the fuels for without after treatment system are illustrated in Figure 4.16.

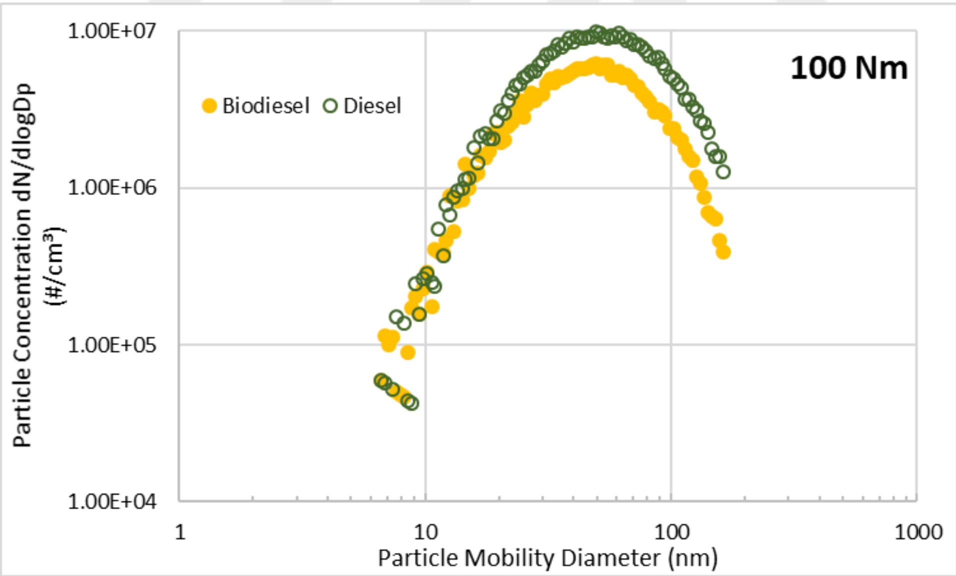


Figure 4.15. Particle concentration variation of the fuels at 100 Nm, 200 Nm and 294 Nm for without after treatment system

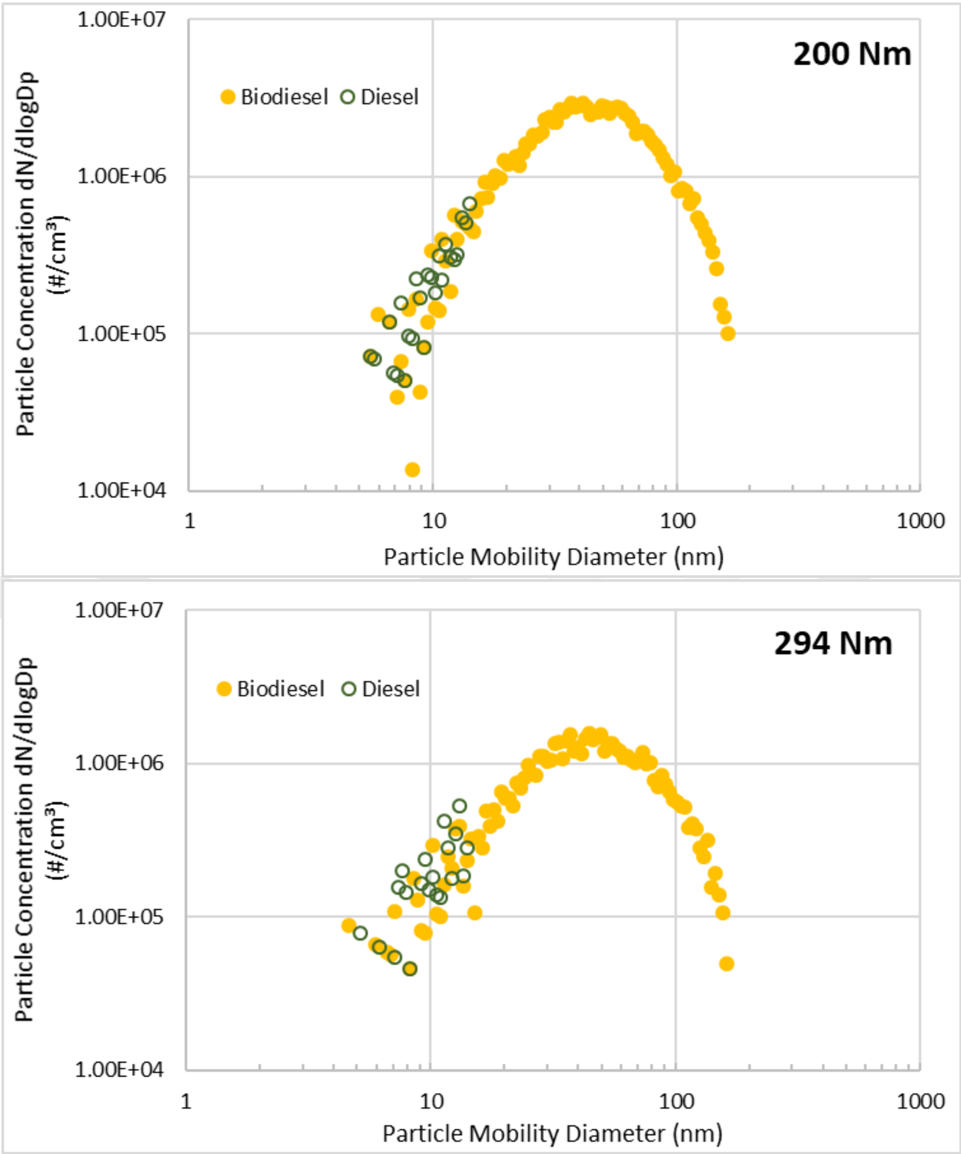


Figure 4.15. Particle concentration variation of the fuels at 100 Nm, 200 Nm and 294 Nm for without after treatment system (Continued)

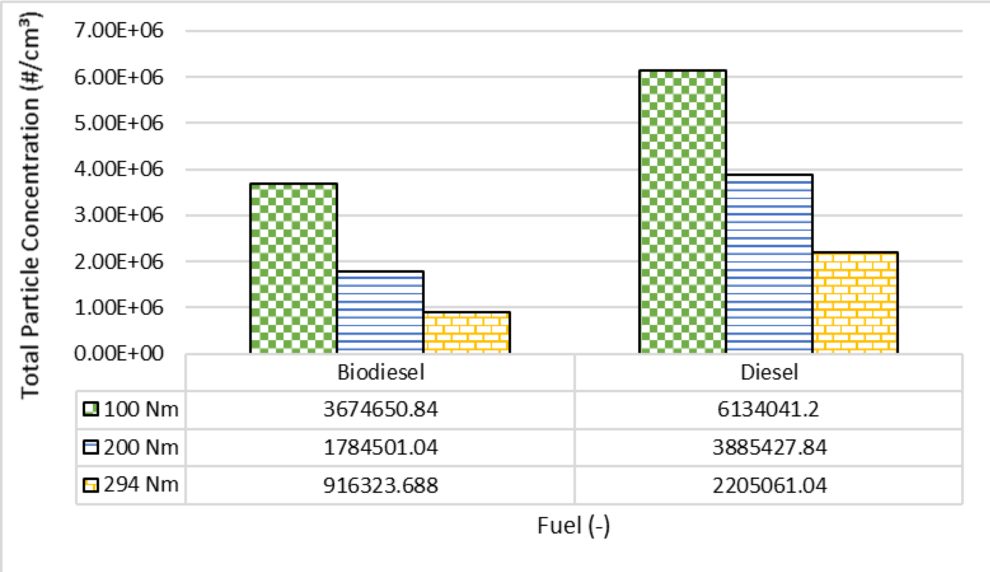


Figure 4.16. Comparison of the total particle concentration changes of the fuels for without after treatment system

If DOC is used alone, particle concentration reduction is not too much for both fuels at 100 Nm load. However, when the engine load is 200 Nm, the particle concentration of the diesel fuel increases from approximately $8x10^5$ $1/cm^3$ to around $8x10^6$ $1/cm^3$, while the particle concentration of biodiesel fuel is close to 100 Nm results. Besides, the particle mobility diameter of the diesel fuel is concentrated around 100 nm for DOC only at 200 Nm load, while it is concentrated approximately between 10 nm and 100 nm for without after treatment system. The minimum total particle concentration is found as 1520881.04 $1/cm^3$ at 200 Nm for the biodiesel fuel and the maximum one is calculated as 5126050.16 $1/cm^3$ at 100 Nm torque for the diesel fuel with DOC only. The variation of particle concentration of the fuels at 100 Nm and 200 Nm for DOC only is shown in Figure 4.17. In addition, the comparison of the total particle concentration changes of the fuels for DOC only are illustrated in Figure 4.18.

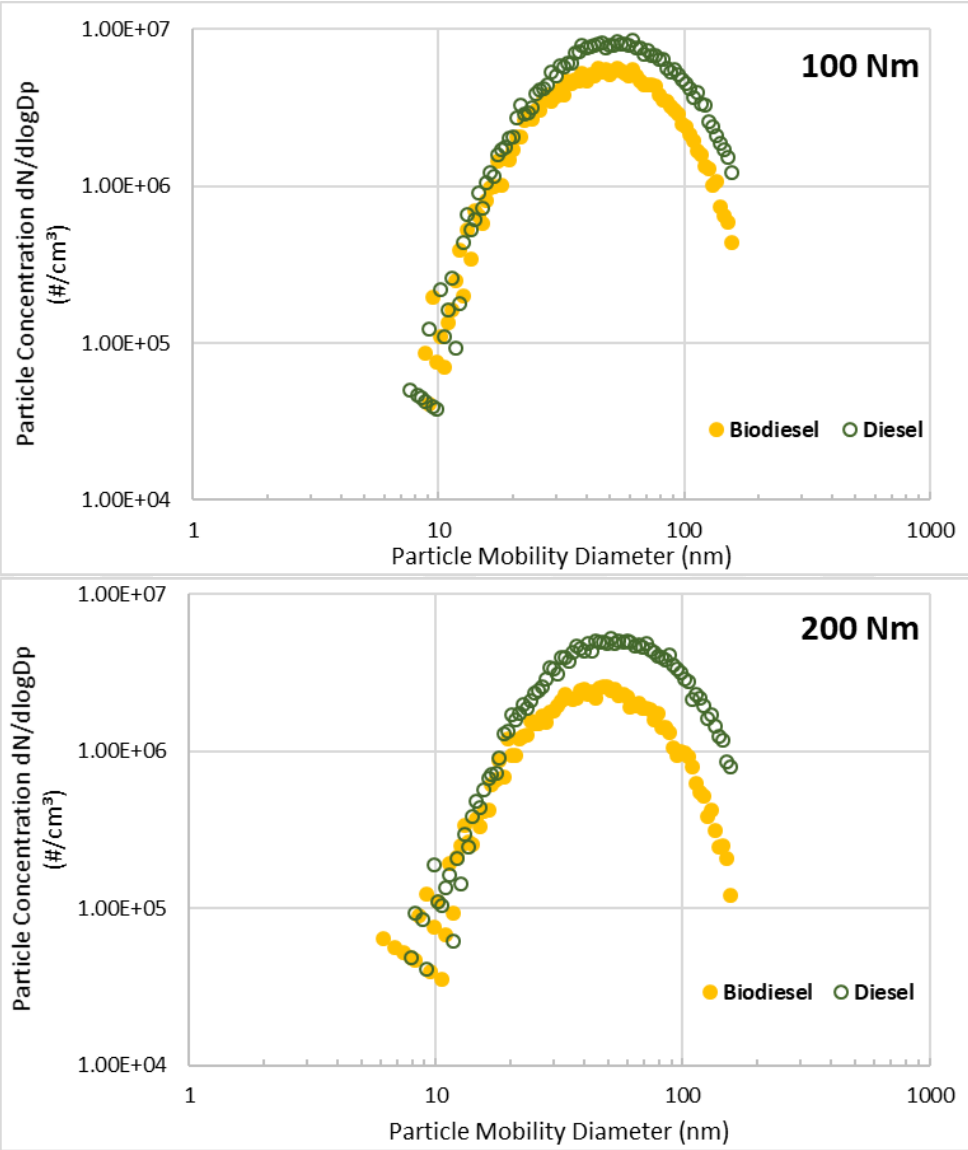
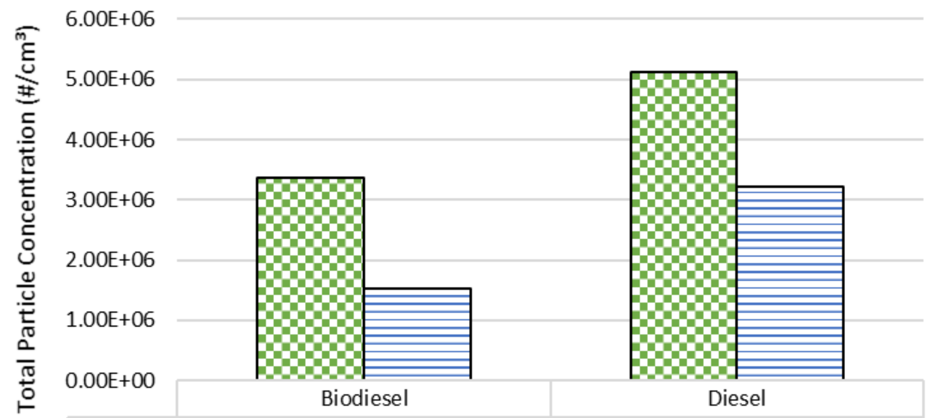


Figure 4.17. Particle concentration variation of the fuels at 100 Nm and 200 Nm load for DOC only



	Biodiesel	Diesel
100 Nm	3355338.84	5126050.16
200 Nm	1520881.04	3219749.12

Figure 4.18. Comparison of the total particle concentration changes of the fuels for DOC only

When SiC DPF after treatment system is used alone, a significant reduction in particle concentration is observed comparing to without after treatment and with DOC only. The minimum 'total' particle concentration is found as 352.45 1/cm^3 for the biodiesel fuel at 200 Nm engine load and the maximum one is determined as 602.99 1/cm^3 for the diesel fuel at 200 Nm engine load. The variation of particle concentration of the fuels at 100 Nm and 200 Nm for SiC only is shown in Figure 4.19. In addition, the comparison of the total particle concentration changes of the fuels for SiC only are given in Figure 4.20.

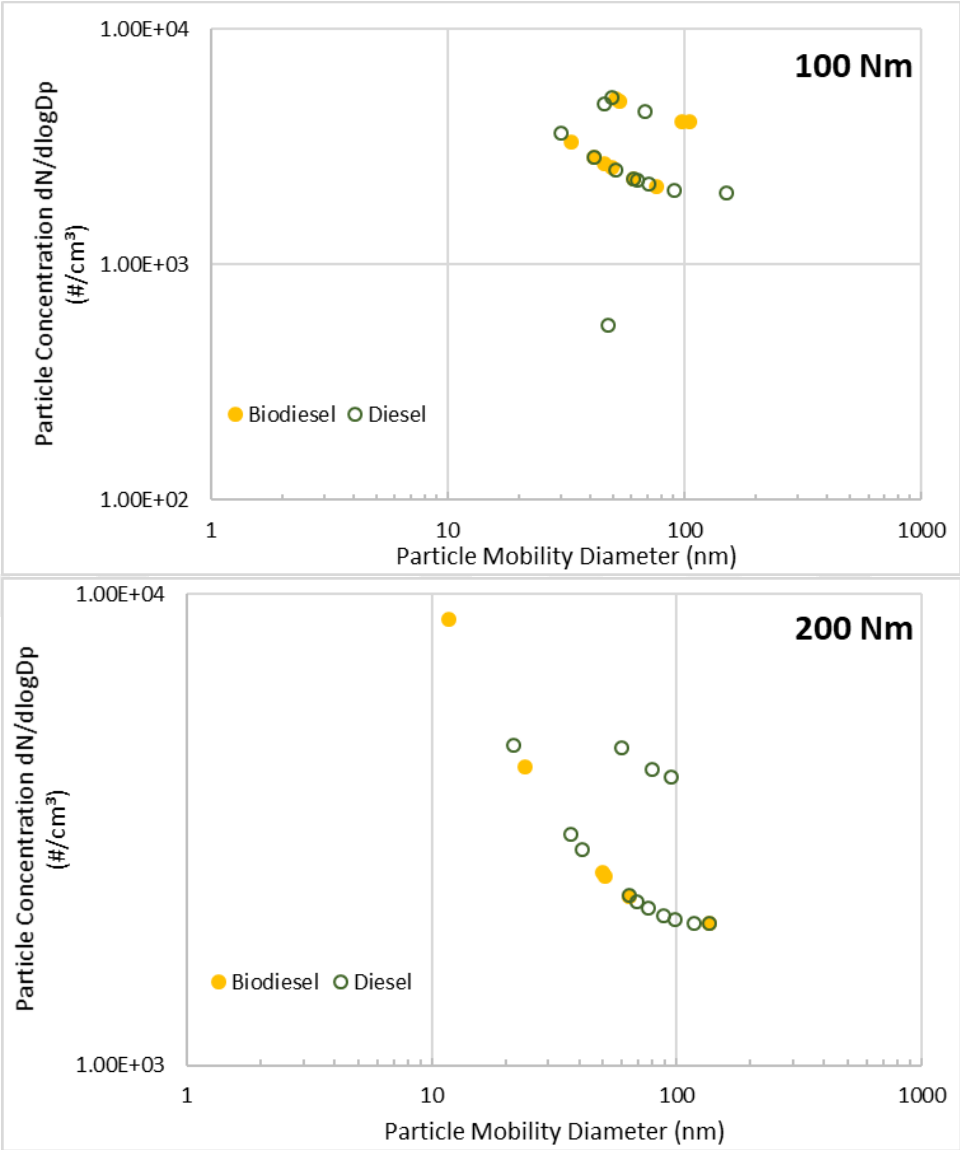


Figure 4.19. Particle concentration variation of the fuels at 100 Nm and 200 Nm load for SiC only

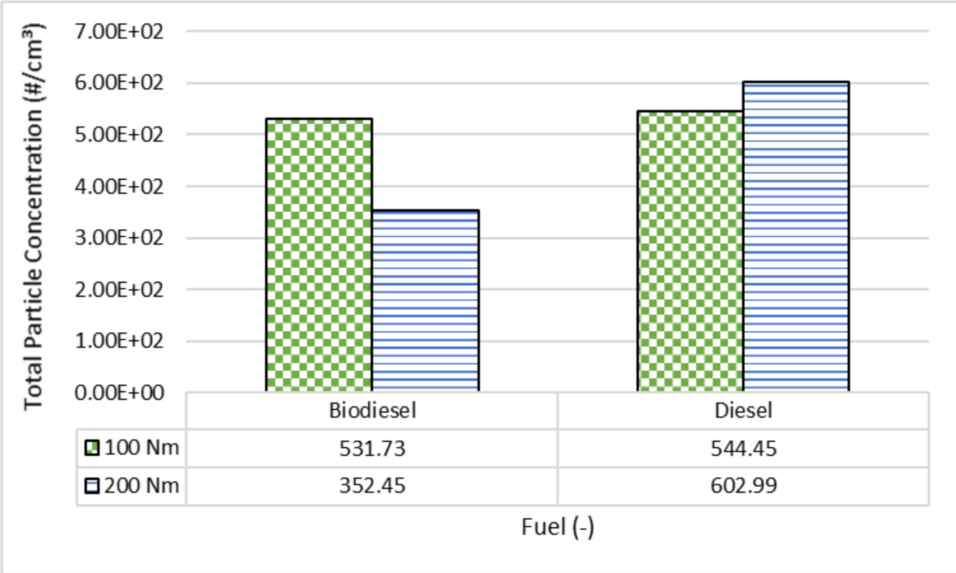


Figure 4.20. Comparison of the total particle concentration changes of the fuels for SiC only

When cordierite DPF after treatment system is used alone, the minimum 'total' particulate concentration is found as 340.53 1/cm^3 for the biodiesel fuel at 100 Nm torque. However, the maximum one is calculated as 707.84 1/cm^3 for the diesel fuel. In this regard, the maximum and minimum total particulate concentration of the cordierite only DPF system is more than SiC only DPF system. The variation of the particle concentration of the fuels at 100 Nm and 200 Nm for cordierite only is given in Figure 4.21. In addition, the comparison of the total particle concentration changes of the fuels for SiC only are shown in Figure 4.22.

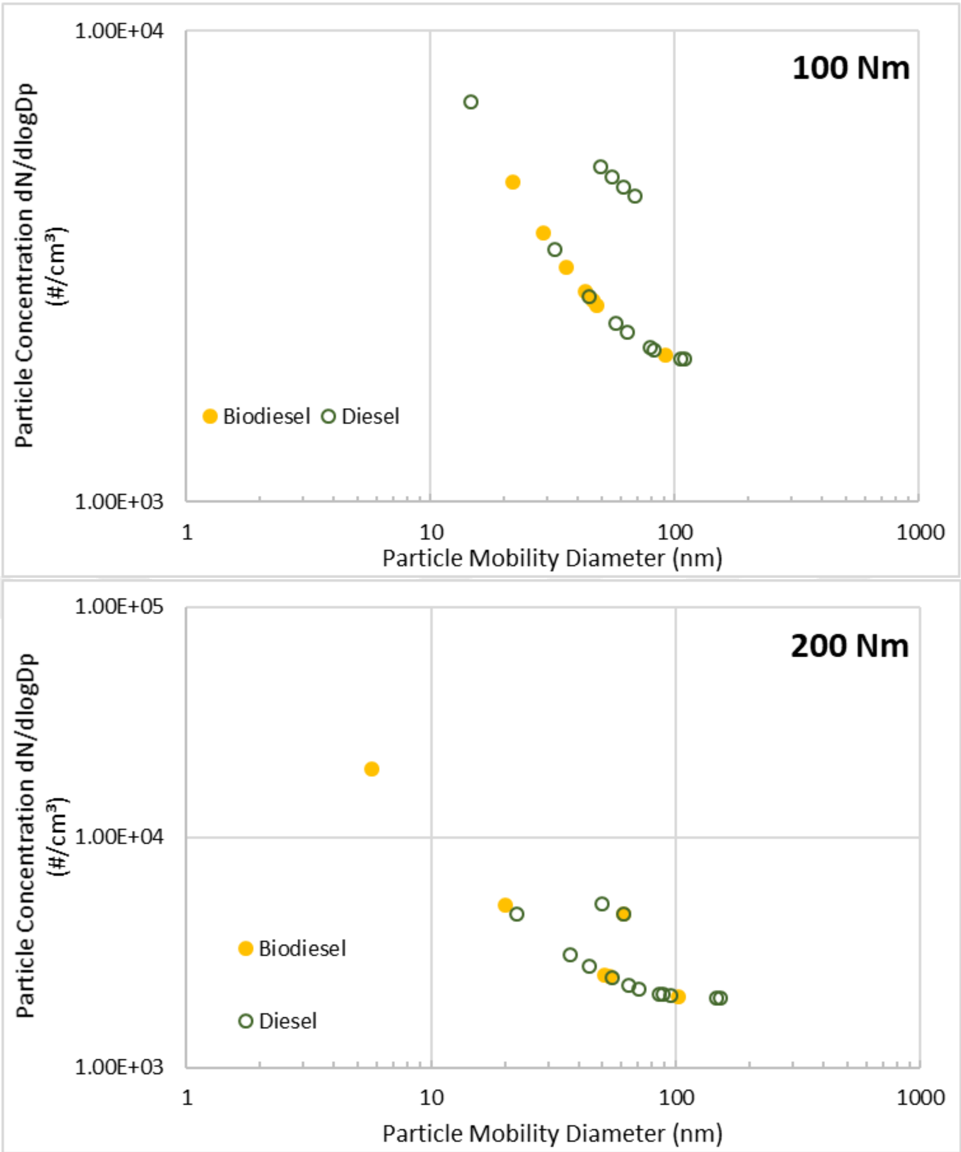


Figure 4.21. Particle concentration variation of the fuels at 100 Nm and 200 Nm load for cordierite only

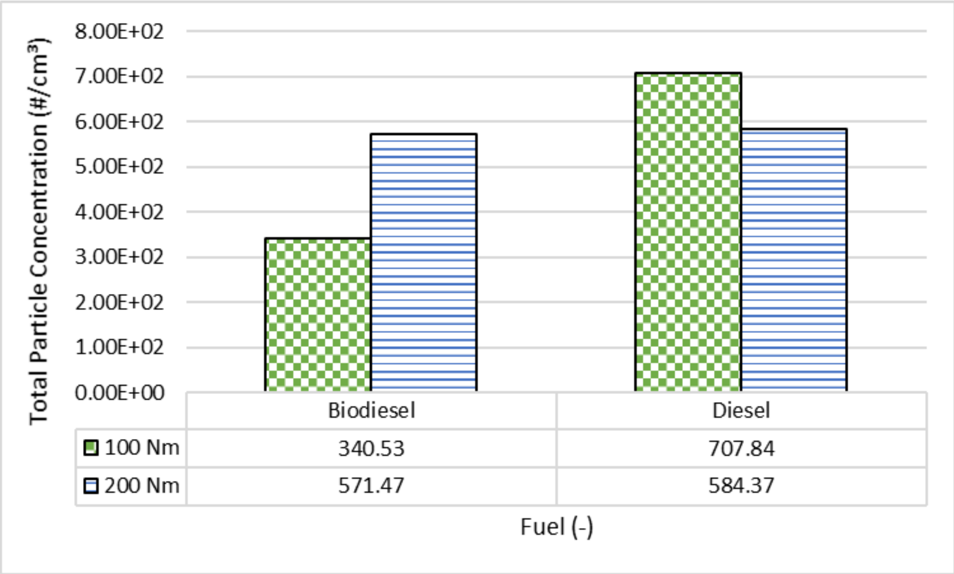


Figure 4.22. Comparison of the total particle concentration changes of the fuels for cordierite only

When DOC is used with SiC DPF (DOC+SiC), the minimum 'total' particle concentration is calculated 527.14 1/cm^3 at 200 Nm torque for the biodiesel fuel and the maximum one is found as 2312.68 1/cm^3 at 100 Nm torque for the diesel. The variation of the particle concentration of the fuels at 100 Nm and 200 Nm for DOC+SiC is shown in Figure 4.23. In addition, the comparison of the total particle concentration changes of the fuels for DOC+SiC are illustrated in Figure 4.24.

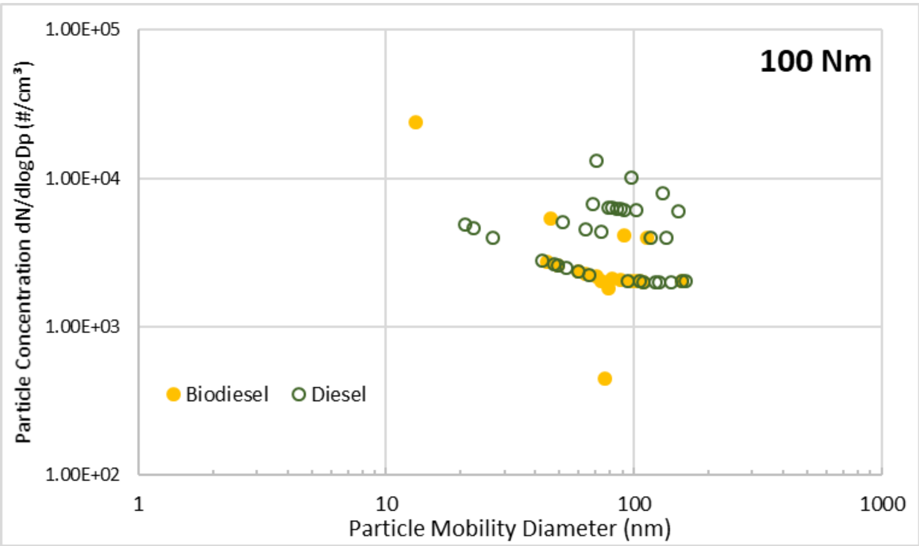


Figure 4.23. Particle concentration variation of the fuels at 100 Nm and 200 Nm load for DOC+SiC

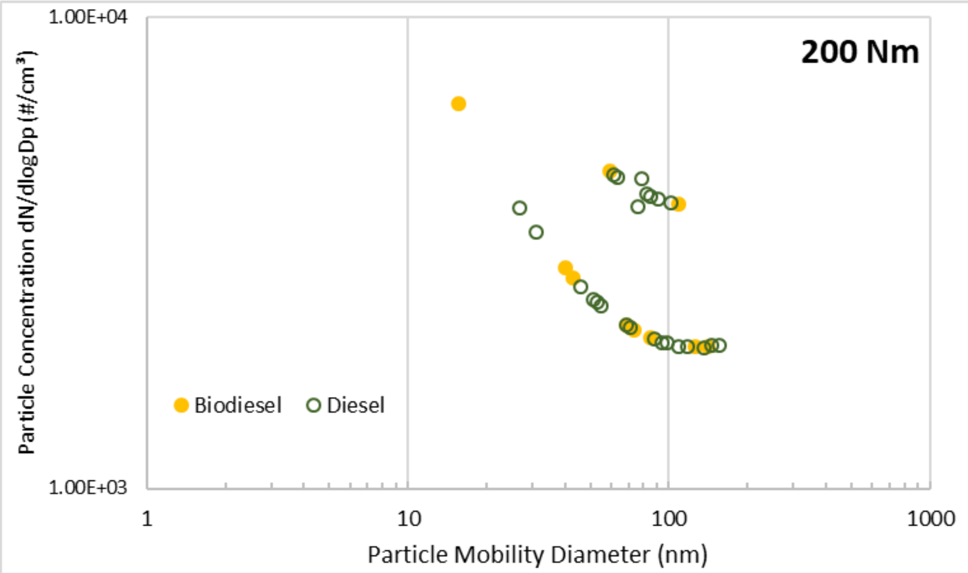


Figure 4.23. Particle concentration variation of the fuels at 100 Nm and 200 Nm load for DOC+SiC (Continued)

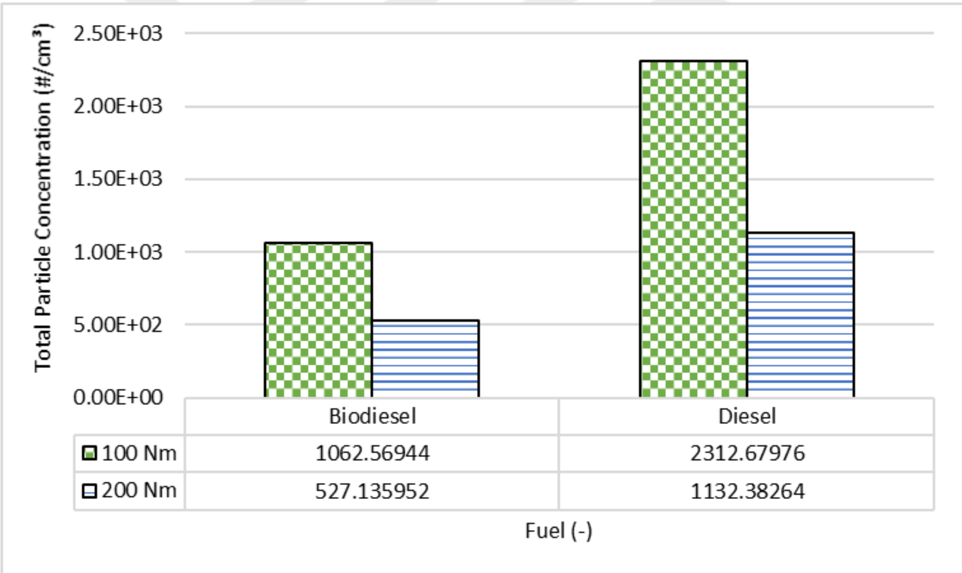


Figure 4.24. Comparison of the total particle concentration changes of the fuels for DOC+SiC

If DOC is used with cordierite diesel particulate filter (DOC+Cordierite), the particle concentration is less than DOC+SiC after treatment system for biodiesel fuel. When the engine is loaded at 100 Nm, the maximum particle concentration of the biodiesel fuel decreases from around $3x10^5$ $1/cm^3$ to $9x10^4$ $1/cm^3$, and the maximum particle concentration of the diesel fuel increases from $2x10^4$ $1/cm^3$ to $4x10^5$ $1/cm^3$at 100 Nm. Besides, when the total particle concentration is examined, the minimum 'total' particle concentration is calculated as 25143.79 1/cm^3 at 200 Nm for the biodiesel fuel and the maximum one is found as 106564.11 1/cm^3 at 100 Nm for the diesel fuel. According to this result, when DOC is used with cordierite, particle size and amounts are more than with SiC diesel particulate filter. The variation of the particle concentration of the fuels at 100 Nm and 200 Nm for DOC+Cordierite is shown in Figure 4.25. In addition, the comparison of the total particle concentration changes of the fuels for DOC+Cordierite are illustrated in Figure 4.26.

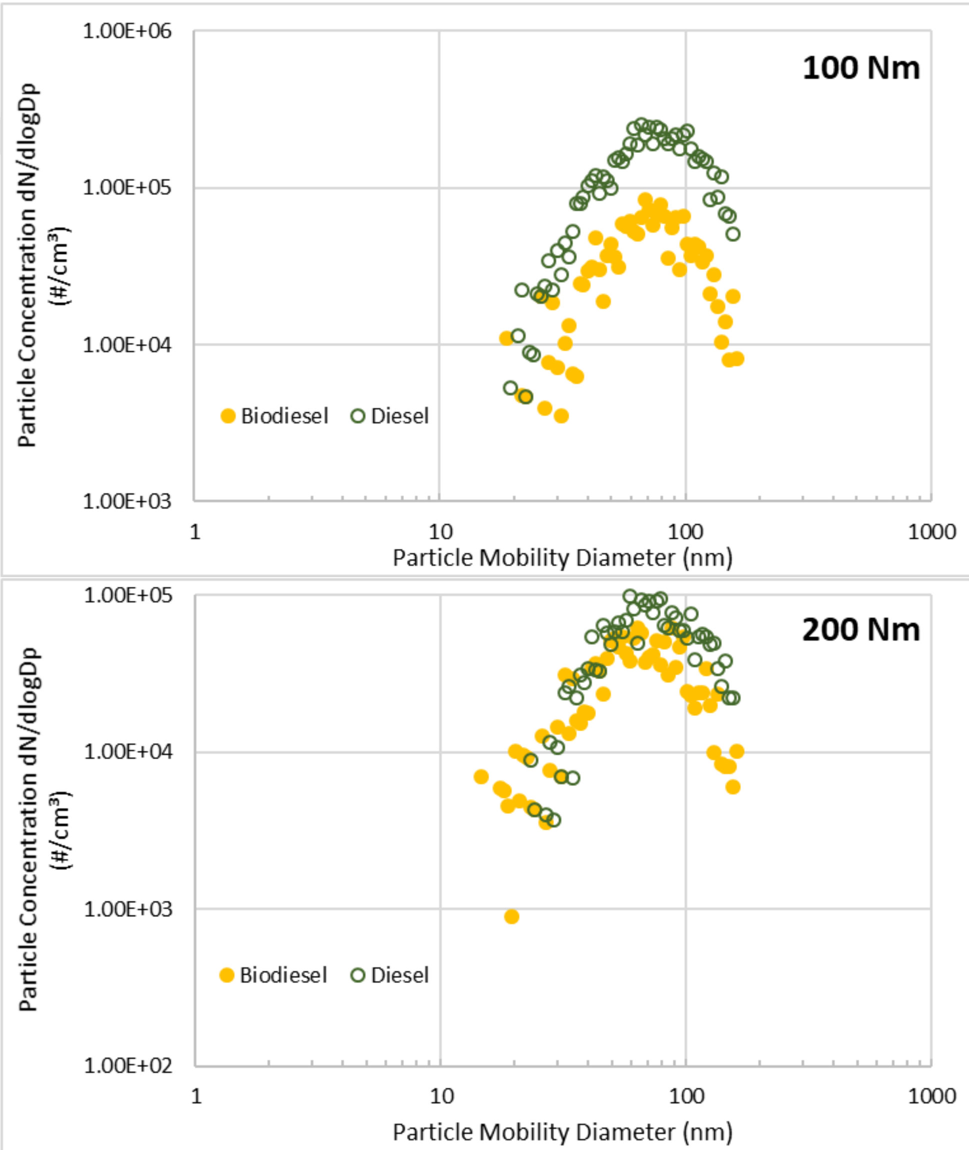
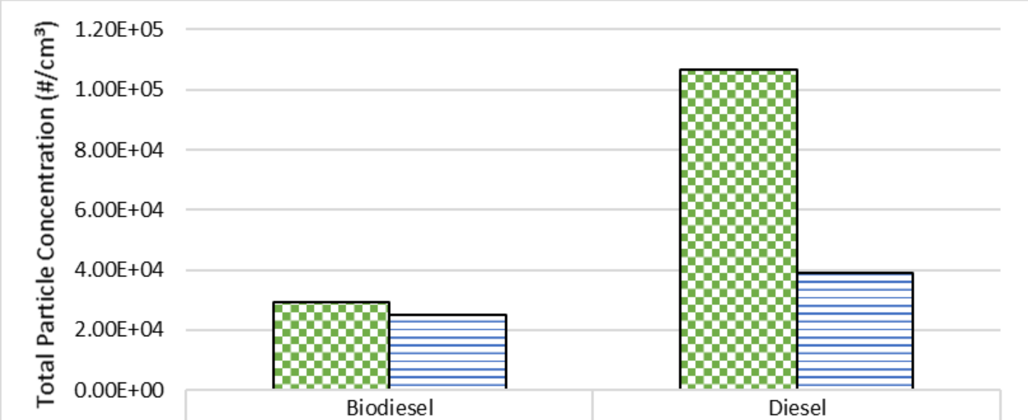


Figure 4.25. Particle concentration variation of the fuels at 100 Nm and 200 Nm load for DOC+Cordierite



	Biodiesel	Diesel
100 Nm	29083.4408	106564.112
200 Nm	25143.792	39097.5536

Figure 4.26. Comparison of the total particle concentration changes of the fuels for DOC+Cordierite

A mass of impure carbon particles originating from the incomplete combustion of hydrocarbons is called as soot. More precisely, it is limited to the product of the gas-phase combustion process, but often it is expanded to include pyrolysis fuel particles [21].

The soot concentration of the biodiesel fuel is usually less than the diesel fuel for without after treatment system. This situation does not change when DOC is used alone. However, DOC is used with SiC or cordierite, the data varies depending on the engine load. If DOC is used with SiC or cordierite, the soot concentration of the biodiesel fuel is more than the diesel fuel at 200Nm load. The minimum soot concentration is calculated as 0.008 mg/m^3 at 200 Nm torque for the biodiesel fuel and the maximum one is found as 2.158 mg/m^3 at 100 Nm torque for the diesel fuel for without after treatment system for SiC only. The soot concentration comparisons of the fuels for with and without after treatment systems are shown in Figure 4.27 through Figure 4.32.

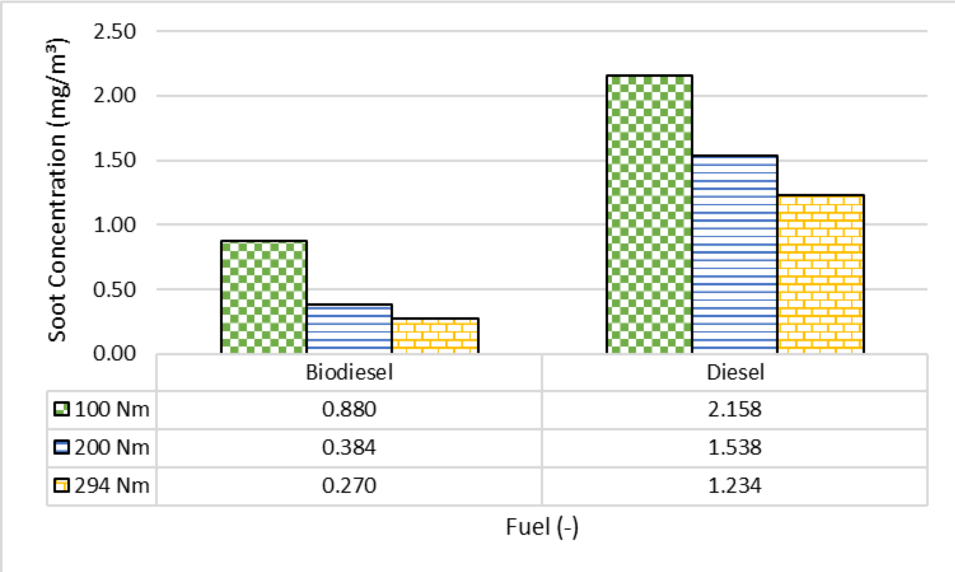


Figure 4.27. Soot concentration comparison of the fuels for without after treatment system

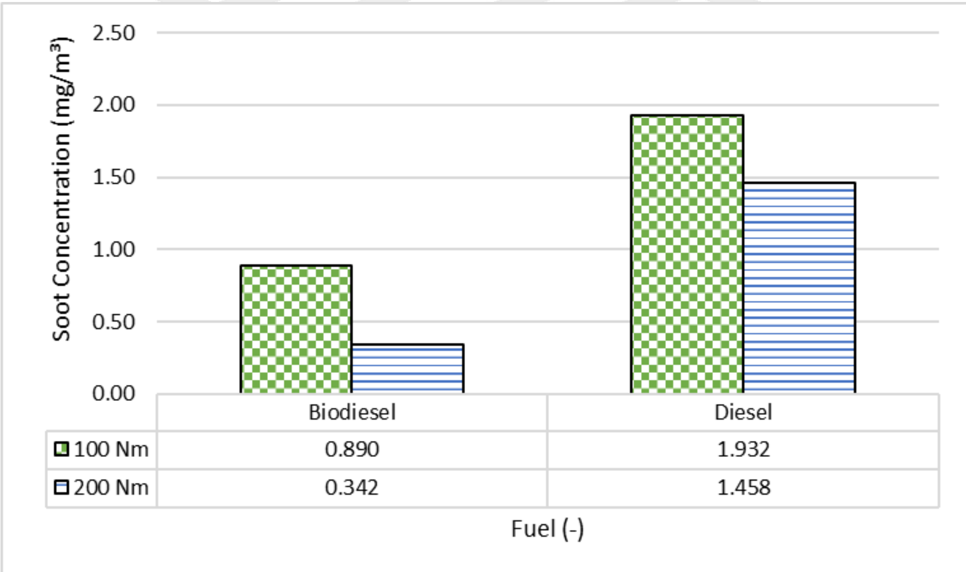


Figure 4.28. Soot concentration comparison of the fuels for DOC only

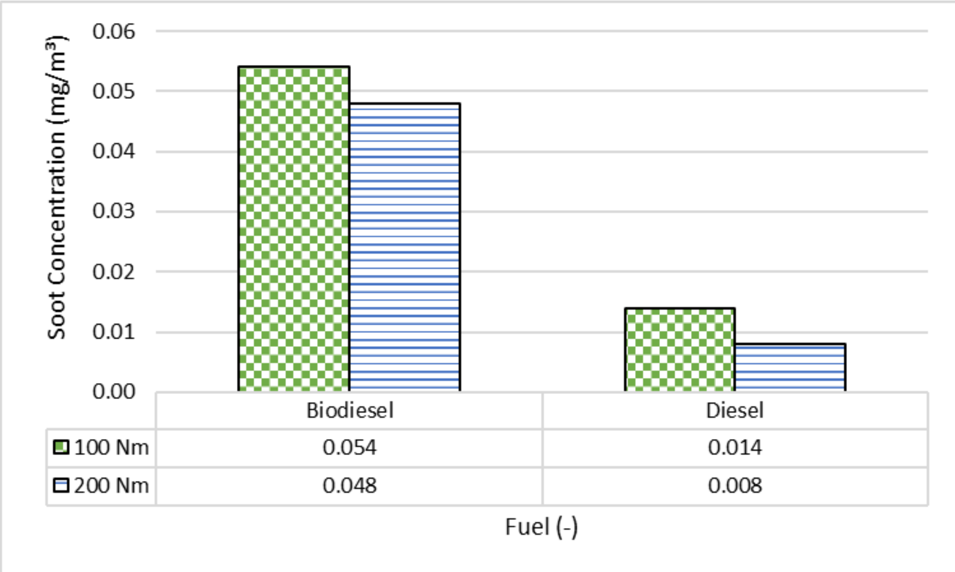


Figure 4.29. Soot concentration comparison of the fuels for SiC only

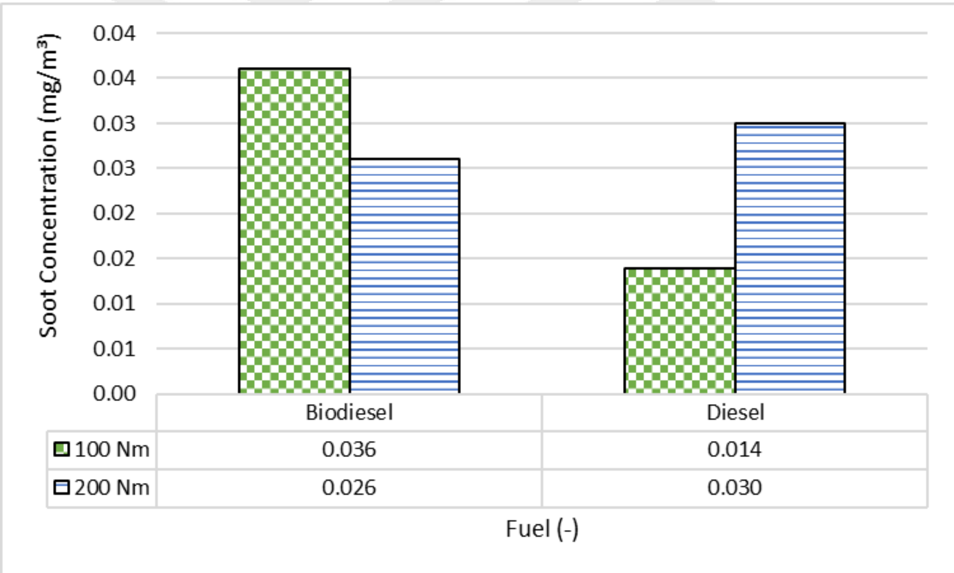


Figure 4.30. Soot concentration comparison of the fuels for cordierite only

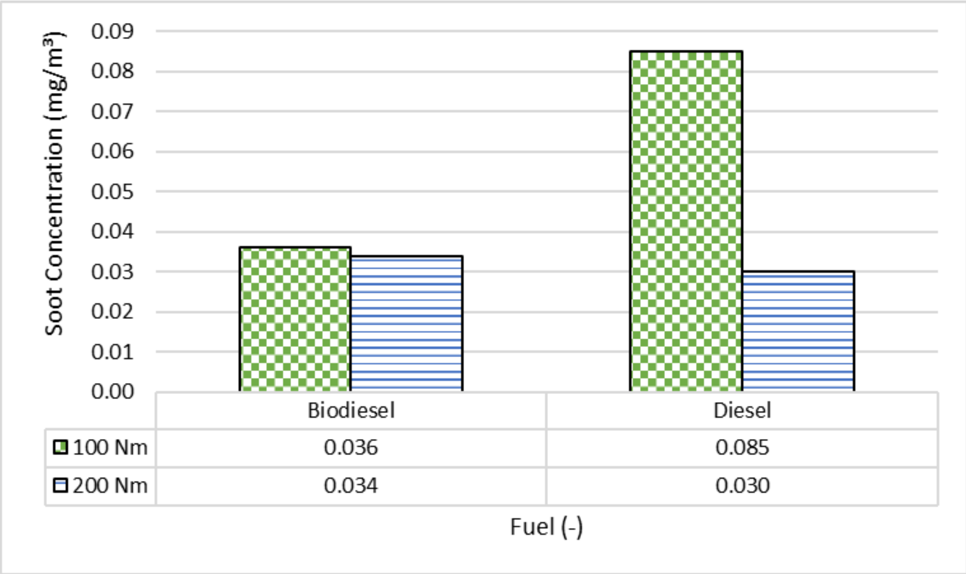


Figure 4.31. Soot concentration comparison of the fuels for DOC+SiC

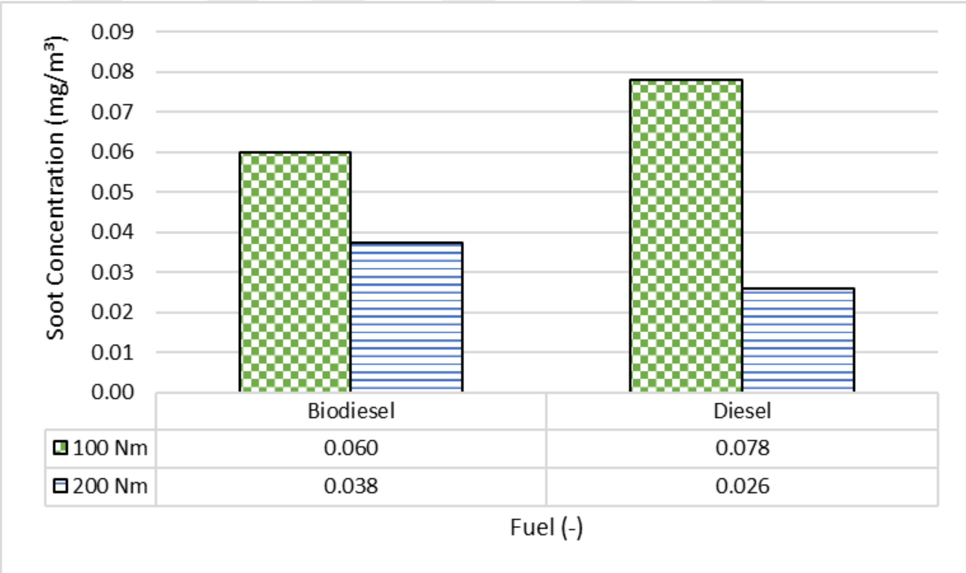


Figure 4.32. Soot concentration comparison of the fuels for DOC+Cordierite

4.2. Energy, Exergy, Sustainability, Environmental, Enviroeconomic, Thermoeconomic and Exergoeconomic Analyses Results

Thermodynamic analysis is applied to the system with and without after treatment options. The energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic and exergoeconomic analyses results of the system for with and without after treatment are tabulated in Table 4.7 through Table 4.12.

Table 4.7. Energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic, exergoeconomic analyses results of the system for without after treatment

	Biodiesel			Diesel		
	100 Nm	200 Nm	294 Nm	100 Nm	200 Nm	294 Nm
Energy Analysis						
Energy rate of air $(\dot{E}n_{air})$ (kW)	12.996	21.081	25.401	12.474	19.712	24.228
Energy rate of fuel $(\dot{E}n_{fuel})$ (kW)	53.268	93.855	124.723	61.430	105.345	145.209
Work rate $(\dot{E}n_W)$ (kW)	18.504	36.980	50.137	19.328	37.292	53.585
Energy rate of exhaust $(\dot{E}n_{exh})$ (kW)	2.104	3.938	5.739	2.062	3.764	5.870
Energy loss rate $(\dot{E}n_{loss})$ (kW)	45.655	74.018	94.247	52.514	84.000	109.983
Energy efficiency (η) (%)	27.925	32.174	33.397	26.152	29.820	31.625
Exergy Analysis						
Exergy rate of air $(\dot{E}x_{air})$ (kW)	0.844 10^{-3}	1.708 10^{-3}	2.288 10^{-3}	0.722 10^{-3}	1.540 10^{-3}	2.071 10^{-3}
Exergy rate of fuel $(\dot{E}x_{fuel})$ (kW)	57.268	100.903	134.090	65.711	112.687	155.330
Work rate $(\dot{E}x_W)$ (kW)	18.504	36.980	50.137	19.328	37.292	53.585
Exergy rate of exhaust $(\dot{E}x_{exh})$ (kW)	1.764	3.273	4.875	1.717	3.104	4.747
Exergy loss rate $(\dot{E}x_{loss})$ (kW)	7.628	12.366	15.750	8.776	14.034	18.395
Exergy rate of destruction $(\dot{E}x_{dest})$ (kW)	29.374	48.286	63.329	35.892	58.259	78.605
Exergy efficiency (ψ) (%)	32.311	36.648	37.390	29.413	33.093	34.497
Entropy generation (S_{gen}) (kW/K)	0.100	0.164	0.215	0.122	0.198	0.267
Environmental Analysis (kg-CO_2/day)						
CO_2 emission (x_{CO_2})	128.165	226.060	300.305	122.891	210.880	290.678
Enviroeconomic Analysis ($/day)						
Enviroeconomic parameter (C_{CO_2})	1.858	3.278	4.354	1.782	3.058	4.215
Sustainability Analysis (-)						
Sustainability analysis result (SI)	1.477	1.578	1.597	1.417	1.495	1.527
Thermoeconomic Analysis (kW/$)						
Thermoeconomic parameter (R_{en})	0.457 10^{-3}	0.740 10^{-3}	0.942 10^{-3}	0.525 10^{-3}	0.840 10^{-3}	1.100 10^{-3}
Exergoeconomic Analysis (kW/$)						
Exergoeconomic analysis result (R_{ex})	0.370 10^{-3}	0.607 10^{-3}	0.791 10^{-3}	0.447 10^{-3}	0.723 10^{-3}	0.970 10^{-3}
Exergoeconomic parameter for loss $(R_{ex,loss})$	0.076 10^{-3}	0.124 10^{-3}	0.158 10^{-3}	0.088 10^{-3}	0.140 10^{-3}	0.184 10^{-3}
Exergoeconomic parameter for destruction $(R_{ex,dest})$	0.294 10^{-3}	0.483 10^{-3}	0.633 10^{-3}	0.359 10^{-3}	0.583 10^{-3}	0.786 10^{-3}

Table 4.8. Energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic, exergoeconomic analyses results of the system for DOC only

	Biodiesel		Diesel	
	100 Nm	200 Nm	100 Nm	200 Nm
Energy Analysis				
Energy rate of air $(\dot{E}n_{air})$ (kW)	13.086	21.824	12.911	20.316
Energy rate of fuel $(\dot{E}n_{fuel})$ (kW)	53.077	96.437	62.714	107.647
Work rate $(\dot{E}n_{W})$ (kW)	18.552	37.107	18.960	37.633
Energy rate of exhaust $(\dot{E}n_{exh})$ (kW)	2.081	4.064	2.082	3.811
Energy loss rate $(\dot{E}n_{loss})$ (kW)	45.530	77.089	54.582	86.519
Energy efficiency (η) (%)	28.039	31.378	25.071	29.409
Exergy Analysis				
Exergy rate of air $(\dot{E}x_{air})$ (kW)	1.368 10^{-3}	1.768 10^{-3}	1.153 10^{-3}	2.386 10^{-3}
Exergy rate of fuel $(\dot{E}x_{fuel})$ (kW)	57.063	103.679	67.085	115.149
Work rate $(\dot{E}x_{W})$ (kW)	18.552	37.107	18.960	37.633
Exergy rate of exhaust $(\dot{E}x_{exh})$ (kW)	1.756	3.378	1.742	3.157
Exergy loss rate $(\dot{E}x_{loss})$ (kW)	7.607	12.894	9.119	14.471
Exergy rate of destruction $(\dot{E}x_{dest})$ (kW)	29.150	50.301	37.265	59.891
Exergy efficiency (ψ) (%)	32.510	35.790	28.263	32.681
Entropy generation (S_{gen}) (kW/K)	0.099	0.171	0.127	0.204
Environmental Analysis (kg-CO_2/day)				
CO_2 emission (x_{CO_2})	128.590	233.714	126.287	216.744
Enviroeconomic Analysis ($/day)				
Enviroeconomic parameter (C_{CO_2})	1.865	3.389	1.831	3.143
Sustainability Analysis (-)				
Sustainability analysis result (SI)	1.482	1.557	1.394	1.485
Thermoeconomic Analysis (kW/$)				
Thermoeconomic parameter (R_{en})	0.455 10^{-3}	0.771 10^{-3}	0.546 10^{-3}	0.865 10^{-3}
Exergoeconomic Analysis (kW/$)				
Exergoeconomic analysis result (R_{ex})	0.368 10^{-3}	0.632 10^{-3}	0.464 10^{-3}	0.744 10^{-3}
Exergoeconomic parameter for loss $(R_{ex,loss})$	0.076 10^{-3}	0.129 10^{-3}	0.091 10^{-3}	0.145 10^{-3}
Exergoeconomic parameter for destruction $(R_{ex,dest})$	0.292 10^{-3}	0.503 10^{-3}	0.373 10^{-3}	0.599 10^{-3}

Table 4.9. Energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic, exergoeconomic analyses results of the system for SiC only

	Biodiesel		Diesel	
	100 Nm	200 Nm	100 Nm	200 Nm
Energy Analysis				
Energy rate of air $(\dot{E}n_{air})$ (kW)	13.037	21.154	12.771	20.129
Energy rate of fuel $(\dot{E}n_{fuel})$ (kW)	52.443	93.649	61.763	106.502
Work rate $(\dot{E}n_{W})$ (kW)	18.550	36.959	18.439	37.218
Energy rate of exhaust $(\dot{E}n_{exh})$ (kW)	2.073	3.956	2.054	3.789
Energy loss rate $(\dot{E}n_{loss})$ (kW)	44.857	73.887	54.041	85.624
Energy efficiency (η) (%)	28.329	32.194	24.739	29.391
Exergy Analysis				
Exergy rate of air $(\dot{E}x_{air})$ (kW)	1.920 10^{-3}	3.730 10^{-3}	1.568 10^{-3}	2.828 10^{-3}
Exergy rate of fuel $(\dot{E}x_{fuel})$ (kW)	56.381	100.682	66.068	113.925
Work rate $(\dot{E}x_{W})$ (kW)	18.550	36.959	18.439	37.218
Exergy rate of exhaust $(\dot{E}x_{exh})$ (kW)	1.742	3.276	1.714	3.131
Exergy loss rate $(\dot{E}x_{loss})$ (kW)	7.500	12.348	9.031	14.309
Exergy rate of destruction $(\dot{E}x_{dest})$ (kW)	28.591	48.103	36.886	59.270
Exergy efficiency (ψ) (%)	32.899	36.708	27.908	32.668
Entropy generation (S_{gen}) (kW/K)	0.097	0.164	0.125	0.201
Environmental Analysis (kg-CO_2/day)				
CO_2 emission (x_{CO_2})	127.107	227.093	124.107	214.316
Enviroeconomic Analysis ($/day)				
Enviroeconomic parameter (C_{CO_2})	1.843	3.293	1.800	3.108
Sustainability Analysis (-)				
Sustainability analysis result (SI)	1.490	1.580	1.387	1.485
Thermoeconomic Analysis (kW/$)				
Thermoeconomic parameter (R_{en})	0.449 10^{-3}	0.739 10^{-3}	0.540 10^{-3}	0.856 10^{-3}
Exergoeconomic Analysis (kW/$)				
Exergoeconomic analysis result (R_{ex})	0.361 10^{-3}	0.605 10^{-3}	0.459 10^{-3}	0.736 10^{-3}
Exergoeconomic parameter for loss $(R_{ex,loss})$	0.075 10^{-3}	0.123 10^{-3}	0.090 10^{-3}	0.143 10^{-3}
Exergoeconomic parameter for destruction $(R_{ex,dest})$	0.286 10^{-3}	0.481 10^{-3}	0.369 10^{-3}	0.593 10^{-3}

Table 4.10. Energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic, exergoeconomic analyses results of the system for cordierite only

	Biodiesel		Diesel	
	100 Nm	200 Nm	100 Nm	200 Nm
Energy Analysis				
Energy rate of air $(\dot{E}n_{air})$ (kW)	13.298	21.734	12.720	20.129
Energy rate of fuel $(\dot{E}n_{fuel})$ (kW)	53.776	96.030	61.730	106.367
Work rate $(\dot{E}n_{W})$ (kW)	18.297	36.713	18.580	37.099
Energy rate of exhaust $(\dot{E}n_{exh})$ (kW)	2.116	4.055	2.057	3.784
Energy loss rate $(\dot{E}n_{loss})$ (kW)	46.661	76.996	53.813	85.613
Energy efficiency (η) (%)	27.279	31.175	24.956	29.328
Exergy Analysis				
Exergy rate of air $(\dot{E}x_{air})$ (kW)	1.693 10^{-3}	3.309 10^{-3}	1.107 10^{-3}	2.139 10^{-3}
Exergy rate of fuel $(\dot{E}x_{fuel})$ (kW)	57.815	103.242	66.033	113.781
Work rate $(\dot{E}x_{W})$ (kW)	18.297	36.713	18.580	37.099
Exergy rate of exhaust $(\dot{E}x_{exh})$ (kW)	1.781	3.350	1.718	3.128
Exergy loss rate $(\dot{E}x_{loss})$ (kW)	7.796	12.874	8.993	14.307
Exergy rate of destruction $(\dot{E}x_{dest})$ (kW)	29.943	50.308	36.743	59.248
Exergy efficiency (ψ) (%)	31.647	35.559	28.137	32.605
Entropy generation (S_{gen}) (kW/K)	0.102	0.171	0.125	0.201
Environmental Analysis (kg-CO_2/day)				
CO_2 emission (x_{CO_2})	130.105	232.726	124.455	214.529
Enviroeconomic Analysis ($/day)				
Enviroeconomic parameter (C_{CO_2})	1.887	3.375	1.805	3.111
Sustainability Analysis (-)				
Sustainability analysis result (SI)	1.463	1.552	1.392	1.484
Thermoeconomic Analysis (kW/$)				
Thermoeconomic parameter (R_{en})	0.455 10^{-3}	0.771 10^{-3}	0.538 10^{-3}	0.856 10^{-3}
Exergoeconomic Analysis (kW/$)				
Exergoeconomic analysis result (R_{ex})	0.377 10^{-3}	0.632 10^{-3}	0.457 10^{-3}	0.736 10^{-3}
Exergoeconomic parameter for loss $(R_{ex,loss})$	0.078 10^{-3}	0.129 10^{-3}	0.090 10^{-3}	0.143 10^{-3}
Exergoeconomic parameter for destruction $(R_{ex,dest})$	0.299 10^{-3}	0.503 10^{-3}	0.367 10^{-3}	0.592 10^{-3}

Table 4.11. Energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic, exergoeconomic analyses results of the system for DOC+SiC

	Biodiesel		Diesel	
	100 Nm	200 Nm	100 Nm	200 Nm
Energy Analysis				
Energy rate of air $(\dot{E}n_{air})$ (kW)	13.369	21.734	12.609	20.035
Energy rate of fuel $(\dot{E}n_{fuel})$ (kW)	54.168	96.030	61.959	107.187
Work rate $(\dot{E}n_{W})$ (kW)	18.523	36.713	18.956	37.329
Energy rate of exhaust $(\dot{E}n_{exh})$ (kW)	2.143	4.055	2.079	3.858
Energy loss rate $(\dot{E}n_{loss})$ (kW)	46.872	76.996	53.533	86.034
Energy efficiency (η) (%)	27.426	31.175	25.421	29.342
Exergy Analysis				
Exergy rate of air $(\dot{E}x_{air})$ (kW)	1.606 10^{-3}	2.718 10^{-3}	1.107 10^{-3}	1.932 10^{-3}
Exergy rate of fuel $(\dot{E}x_{fuel})$ (kW)	58.082	101.996	65.990	114.160
Work rate $(\dot{E}x_{W})$ (kW)	18.523	37.157	18.956	37.329
Exergy rate of exhaust $(\dot{E}x_{exh})$ (kW)	1.802	3.117	1.736	3.285
Exergy loss rate $(\dot{E}x_{loss})$ (kW)	7.834	12.626	8.947	14.388
Exergy rate of destruction $(\dot{E}x_{dest})$ (kW)	29.925	49.100	36.352	59.161
Exergy efficiency (ψ) (%)	31.890	36.428	28.725	32.698
Entropy generation (S_{gen}) (kW/K)	0.102	0.167	0.124	0.201
Environmental Analysis (kg-CO_2/day)				
CO_2 emission (x_{CO_2})	131.409	230.677	125.024	216.349
Enviroeconomic Analysis ($/day)				
Enviroeconomic parameter (C_{CO_2})	1.905	3.345	1.813	3.137
Sustainability Analysis (-)				
Sustainability analysis result (SI)	1.468	1.573	1.403	1.486
Thermoeconomic Analysis (kW/$)				
Thermoeconomic parameter (R_{en})	0.469 10^{-3}	0.755 10^{-3}	0.535 10^{-3}	0.860 10^{-3}
Exergoeconomic Analysis (kW/$)				
Exergoeconomic analysis result (R_{ex})	0.378 10^{-3}	0.617 10^{-3}	0.453 10^{-3}	0.735 10^{-3}
Exergoeconomic parameter for loss $(R_{ex,loss})$	0.078 10^{-3}	0.126 10^{-3}	0.089 10^{-3}	0.144 10^{-3}
Exergoeconomic parameter for destruction $(R_{ex,dest})$	0.299 10^{-3}	0.491 10^{-3}	0.364 10^{-3}	0.592 10^{-3}

Table 4.12. Energy, exergy, sustainability, environmental, enviroeconomic, thermoeconomic, exergoeconomic analyses results of the system for DOC+Cordierite

	Biodiesel		Diesel	
	100 Nm	200 Nm	100 Nm	200 Nm
Energy Analysis				
Energy rate of air $(\dot{E}n_{air})$ (kW)	13.289	21.484	12.826	20.405
Energy rate of fuel $(\dot{E}n_{fuel})$ (kW)	54.042	95.077	62.777	108.368
Work rate $(\dot{E}n_{W})$ (kW)	18.954	36.996	19.073	37.272
Energy rate of exhaust $(\dot{E}n_{exh})$ (kW)	2.151	3.938	2.107	3.874
Energy loss rate $(\dot{E}n_{loss})$ (kW)	46.226	75.626	54.422	87.628
Energy efficiency (η) (%)	28.150	31.740	25.228	28.944
Exergy Analysis				
Exergy rate of air $(\dot{E}x_{air})$ (kW)	2.327 10^{-3}	3.925 10^{-3}	1.021 10^{-3}	2.051 10^{-3}
Exergy rate of fuel $(\dot{E}x_{fuel})$ (kW)	57.947	101.946	66.861	115.418
Work rate $(\dot{E}x_{W})$ (kW)	18.954	36.996	19.073	37.272
Exergy rate of exhaust $(\dot{E}x_{exh})$ (kW)	1.806	3.161	1.760	3.202
Exergy loss rate $(\dot{E}x_{loss})$ (kW)	7.728	12.644	9.096	14.663
Exergy rate of destruction $(\dot{E}x_{dest})$ (kW)	29.461	49.149	36.933	60.284
Exergy efficiency (ψ) (%)	32.708	36.289	28.526	32.292
Entropy generation (S_{gen}) (kW/K)	0.100	0.167	0.126	0.205
Environmental Analysis (kg-CO_2/day)				
CO_2 emission (x_{CO_2})	131.392	231.173	126.925	218.789
Enviroeconomic Analysis ($/day)				
Enviroeconomic parameter (C_{CO_2})	1.905	3.352	1.840	3.172
Sustainability Analysis (-)				
Sustainability analysis result (SI)	1.486	1.570	1.399	1.477
Thermoeconomic Analysis (kW/$)				
Thermoeconomic parameter (R_{en})	0.462 10^{-3}	0.756 10^{-3}	0.544 10^{-3}	0.876 10^{-3}
Exergoeconomic Analysis (kW/$)				
Exergoeconomic analysis result (R_{ex})	0.372 10^{-3}	0.618 10^{-3}	0.460 10^{-3}	0.749 10^{-3}
Exergoeconomic parameter for loss $(R_{ex,loss})$	0.077 10^{-3}	0.126 10^{-3}	0.091 10^{-3}	0.147 10^{-3}
Exergoeconomic parameter for destruction $(R_{ex,dest})$	0.295 10^{-3}	0.491 10^{-3}	0.369 10^{-3}	0.603 10^{-3}

Energy analysis results of the system are directly proportional to the engine loads. If the engine load increases, the energy rates are also increase. The energy rates of air, fuel, work, exhaust, loss, and energy efficiency of the system are calculated as maximum at 294 Nm for without after treatment system and 200 Nm load for after treatment system, while the minimum ones are found at 100 Nm torque for both of the fuels. In addition, all of the minimum energy rates are obtained from the biodiesel fuel, while the diesel fuel has the maximum rates. Moreover, the energy rates of losses from maximum to minimum are found as DOC+SiC>Cordierite only>DOC+Cordierite>Engine Out (before after treatment unit)>DOC only>SiC only for the biodiesel fuel. Also, the energy rates of losses from maximum to minimum are calculated to be DOC only>DOC+Cordierite>SiC only>cordierite only>DOC+SiC>Engine Out for the diesel fuel. Although the diesel fuel generates more exhaust emissions energy output in the system, the biodiesel fuel is a better option. Because, it produces lower exhaust emissions than the diesel fuel. On the other hand, if biodiesel fuel is used in the diesel engine, its energy efficiency is better than diesel fuel at every engine loads. The energy analysis results of the system and the energy efficiency comparison of the system for with and without after treatment are shown in Figure 4.33 through Figure 4.44.

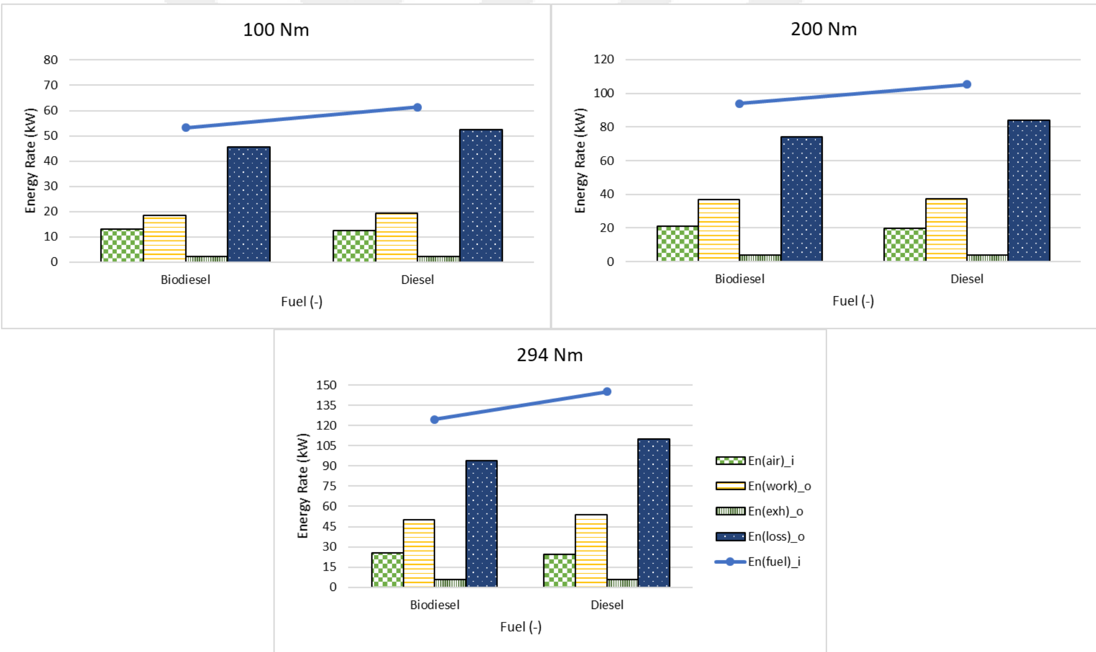


Figure 4.33. Energy analysis results of the system for without after treatment

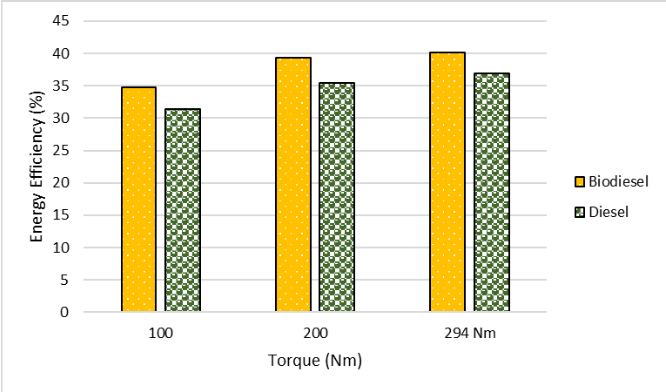


Figure 4.34. Energy efficiency comparison of the system for without after treatment

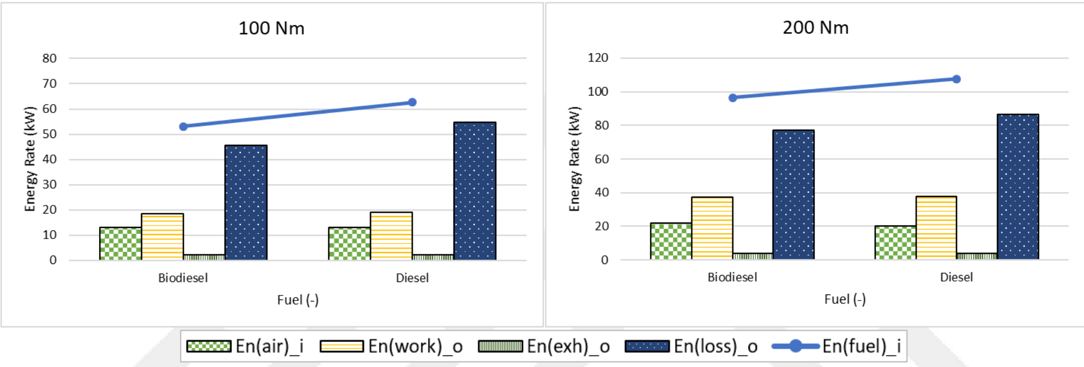


Figure 4.35. Energy analysis results of the system for DOC only

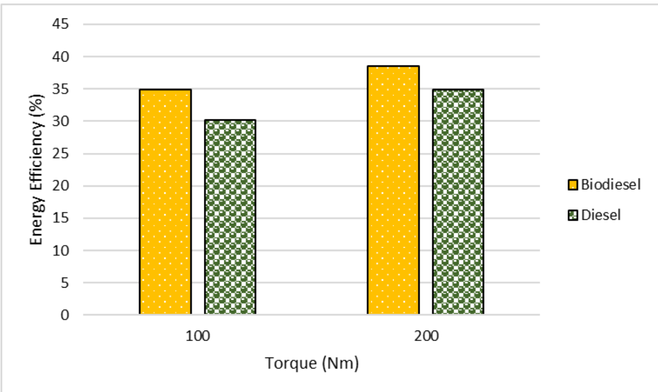


Figure 4.36. Energy efficiency comparison of the system for DOC only

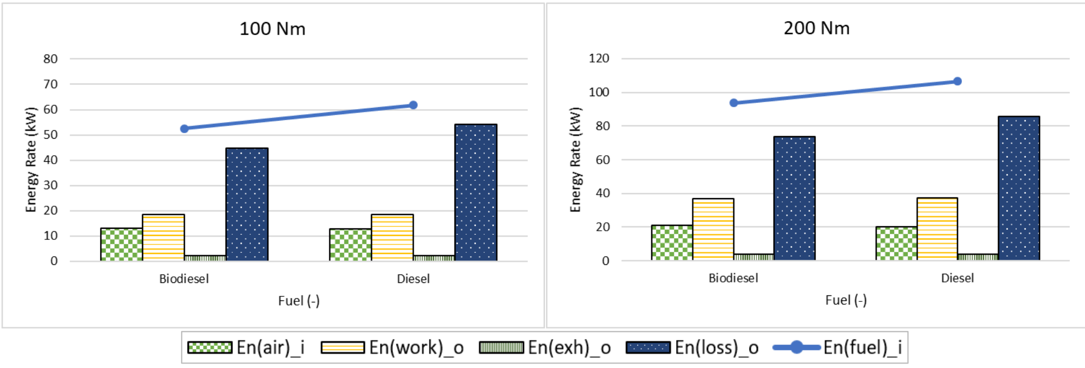


Figure 4.37. Energy analysis results of the system for SiC only

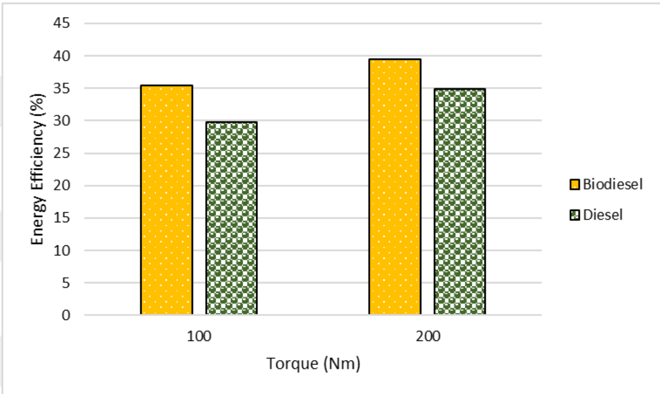


Figure 4.38. Energy efficiency comparison of the system for SiC only

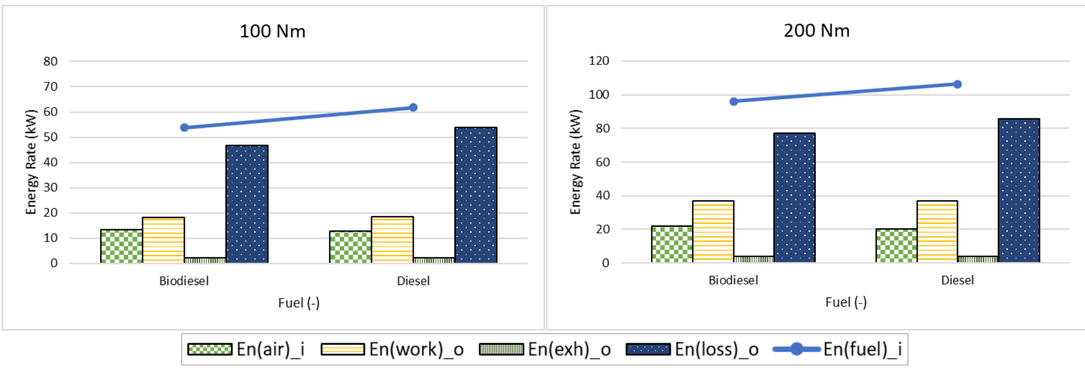


Figure 4.39. Energy analysis results of the system for cordierite only

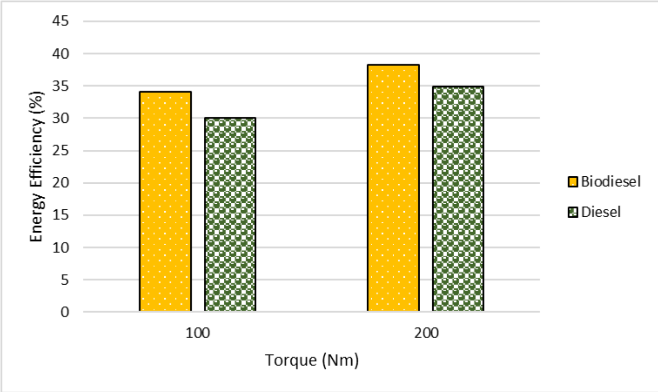


Figure 4.40. Energy efficiency comparison of the system for cordierite only

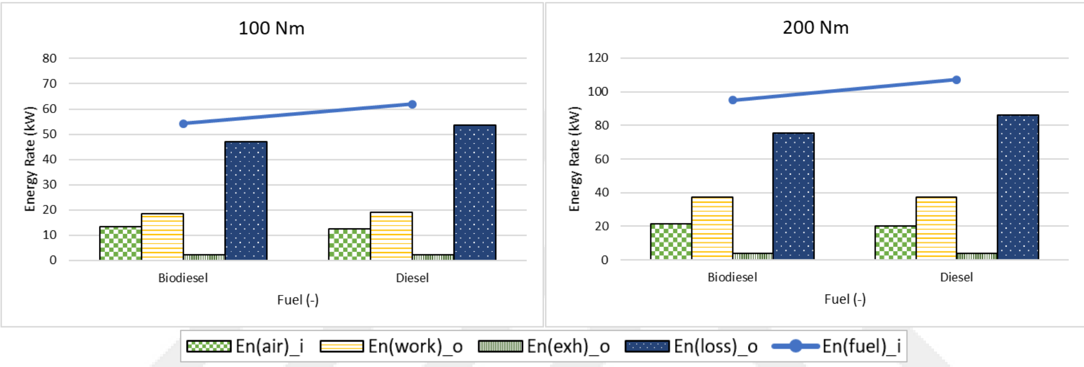


Figure 4.41. Energy analysis results of the system for DOC+SiC

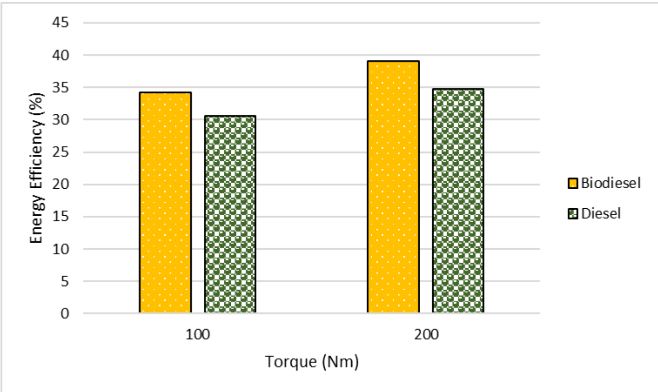


Figure 4.42. Energy efficiency comparison of the system for DOC+SiC

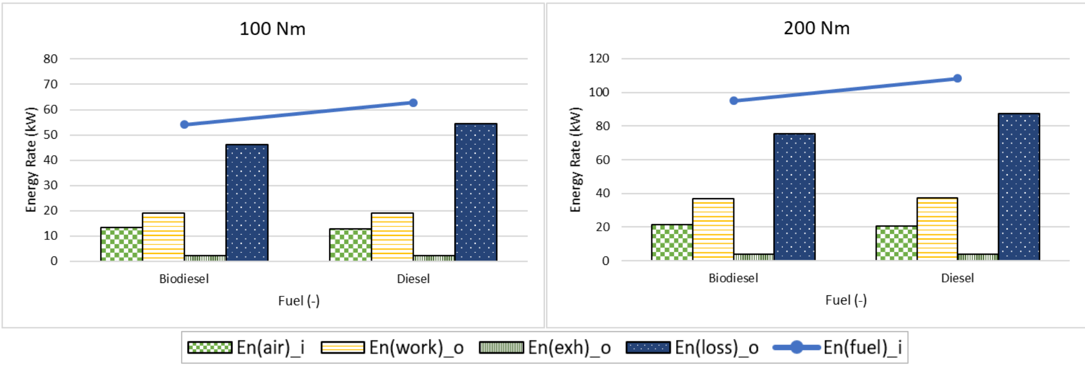


Figure 4.43. Energy analysis results of the system for DOC+Cordierite

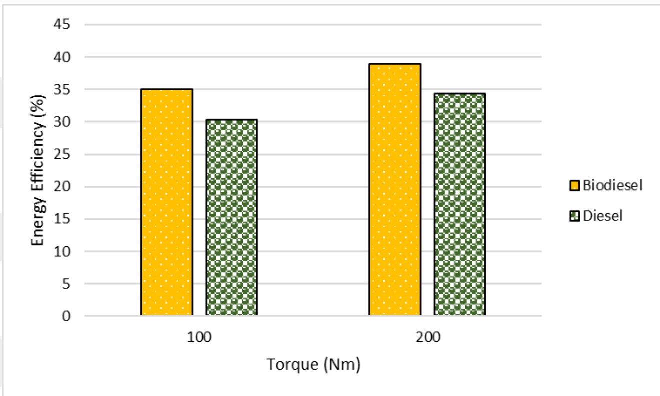


Figure 4.44. Energy efficiency comparison of the system for DOC+Cordierite

The exergy rates are also directly proportional to the engine load. For both of the fuels, the minimum exergy rates of air, fuel, work, exhaust, loss, destruction and exergy efficiency of the system are calculated at 100 Nm. The maximum exergy input rate of air and exergy output rate of exhaust gases are found for the biodiesel fuel for with and without after treatment systems. Also, the maximum exergy efficiency rates are calculated for the biodiesel fuel for with and without after treatment systems. The exergy rates of the systems for the biodiesel fuel from maximum to minimum are as follows: DOC+SiC>DOC+Cordierite>cordierite only>Engine Out>DOC only>SiC only. Indeed, the exergy rates of the systems for the diesel fuel from maximum to minimum are DOC only>DOC+Cordierite>SiC only>cordierite>DOC+SiC>Engine Out. The chemical formula and chemical exergy factors play important role on exergy rate of fuel. The exergy rates of losses and destructions of the biodiesel fuel are less than the diesel fuel. Since the diesel fuel causes more exhaust emission, exergy and exergy destruction in the system, the biodiesel fuel is better for the emission and exergy destruction optimization.

On the other hand, biodiesel fuels are better option than diesel fuels for better exergy efficiency at every engine loads. The exergy efficiency of the system for the biodiesel fuel from maximum to minimum are as follows: SiC only>DOC+Cordierite>DOC only>Engine Out>DOC+SiC>cordierite only. Also, the exergy efficiency of the system for the diesel fuel from maximum to minimum are Engine Out>DOC+SiC>DOC+Cordierite>DOC only>cordierite only> SiC only. The exergy analysis results of the system and the energy efficiency comparison of the system for with and without after treatment are illustrated in Figure 4.45 through Figure 4.56.

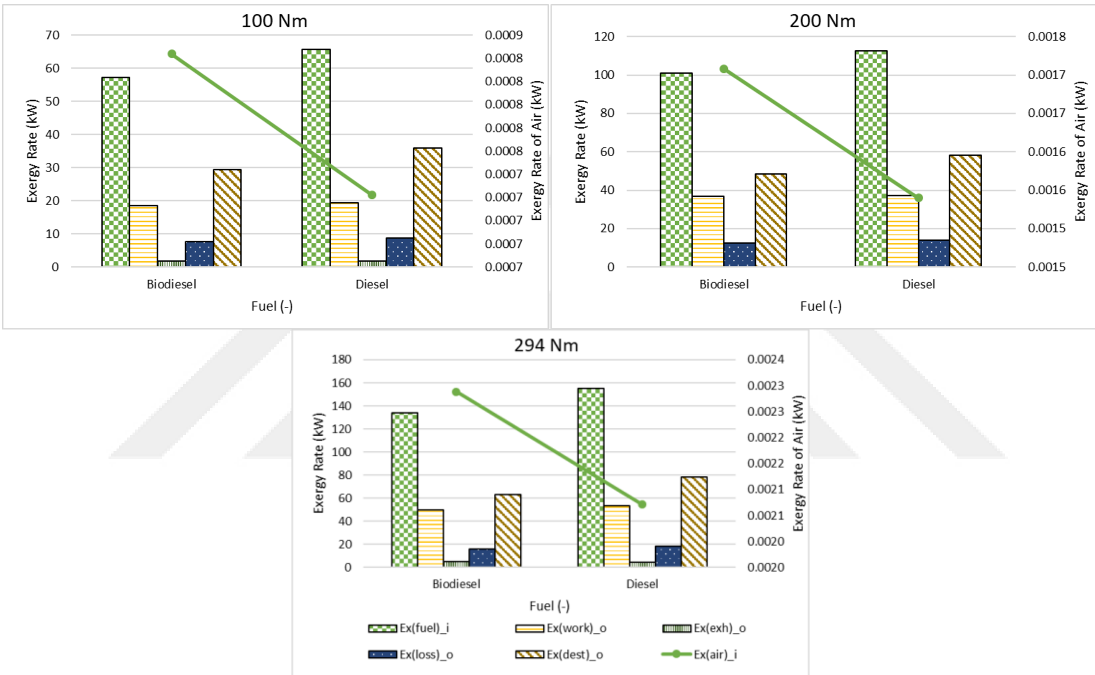


Figure 4.45. Exergy analysis results of the system for without after treatment system

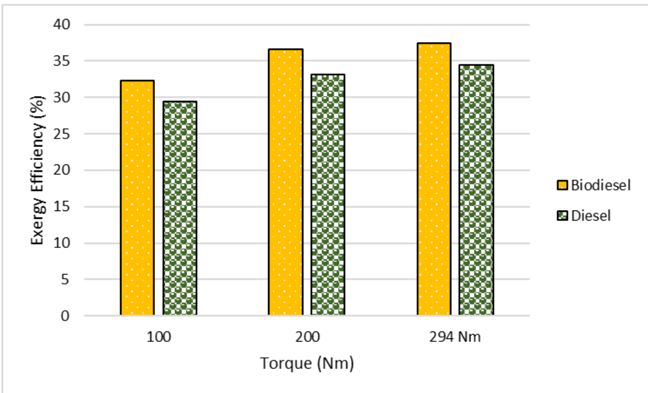


Figure 4.46. Exergy efficiency comparison of the system for without after treatment system

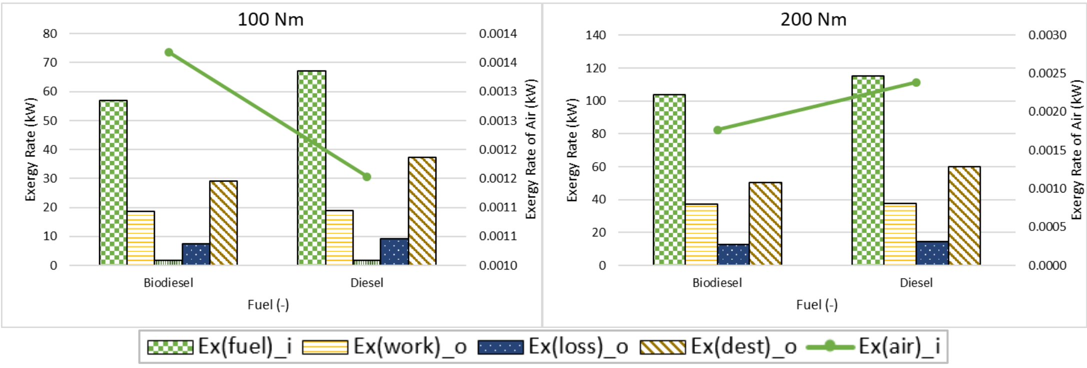


Figure 4.47. Exergy analysis results of the system for DOC only

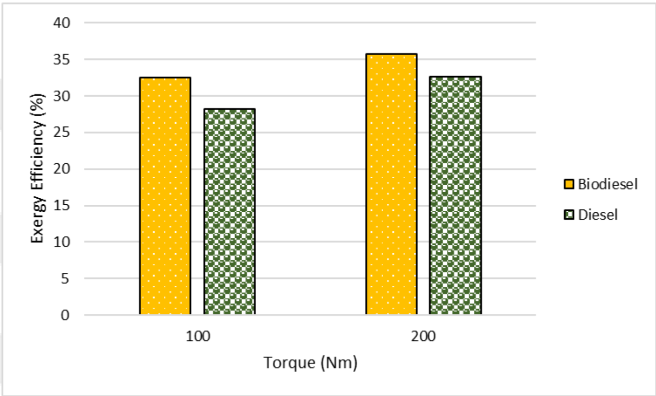


Figure 4.48. Exergy efficiency comparison of the system for DOC only

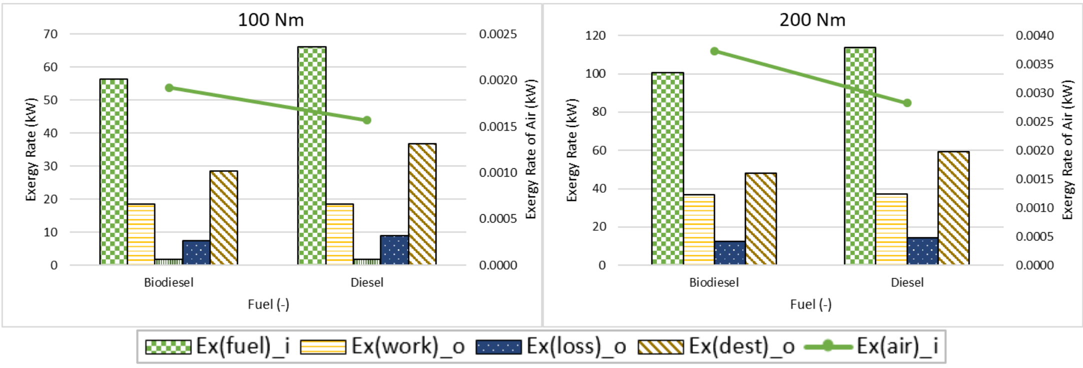


Figure 4.49. Exergy analysis results of the system for SiC only

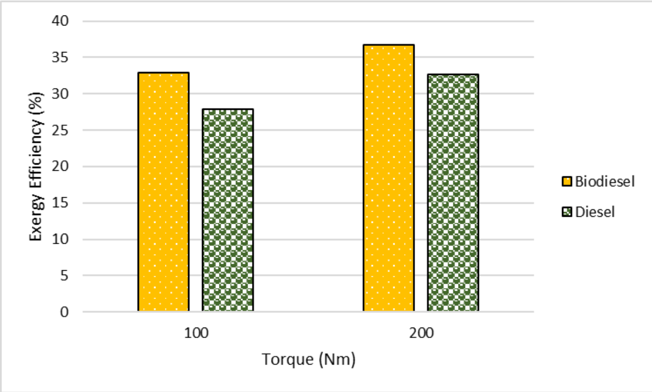


Figure 4.50. Exergy efficiency comparison of the system for SiC only

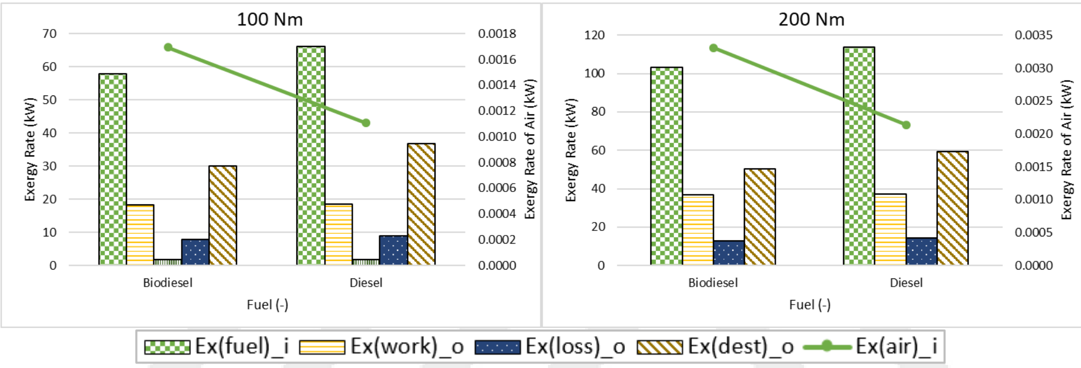


Figure 4.51. Exergy analysis results of the system for cordierite only

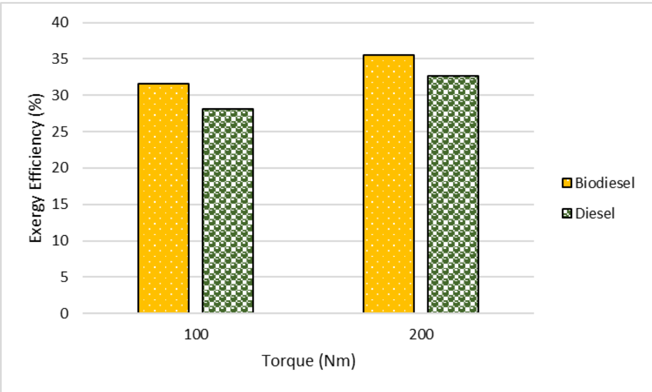


Figure 4.52. Exergy efficiency comparison of the system for cordierite only

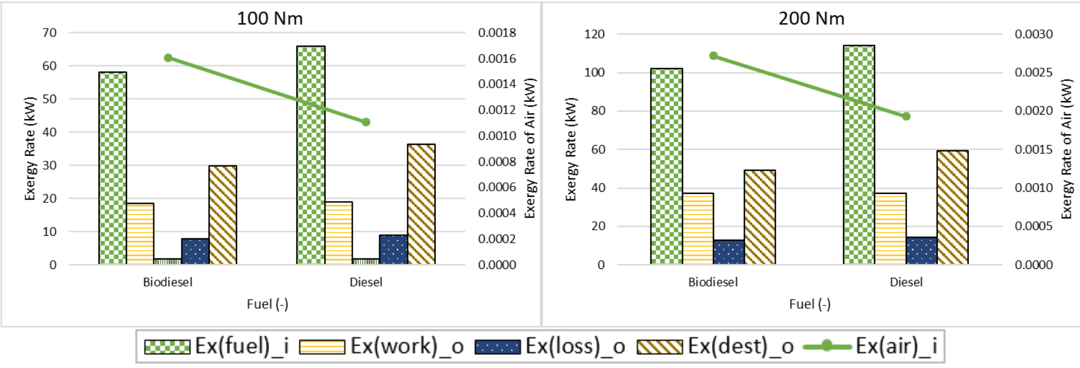


Figure 4.53. Exergy analysis results of the system for DOC+SiC

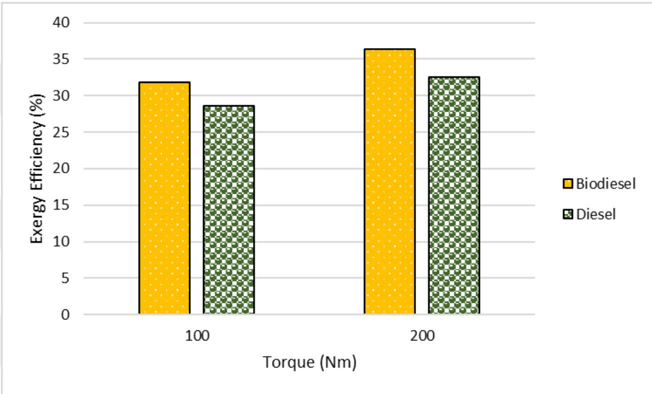


Figure 4.54. Exergy efficiency comparison of the system for DOC+SiC

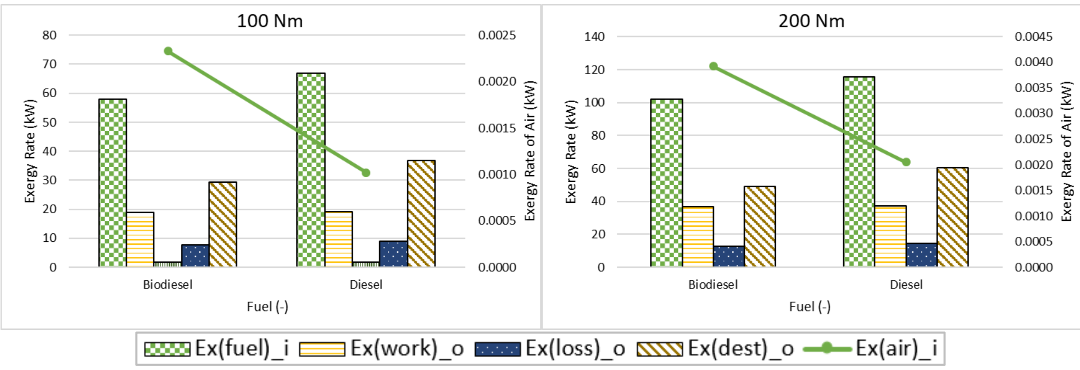


Figure 4.55. Exergy analysis results of the system for DOC+Cordierite

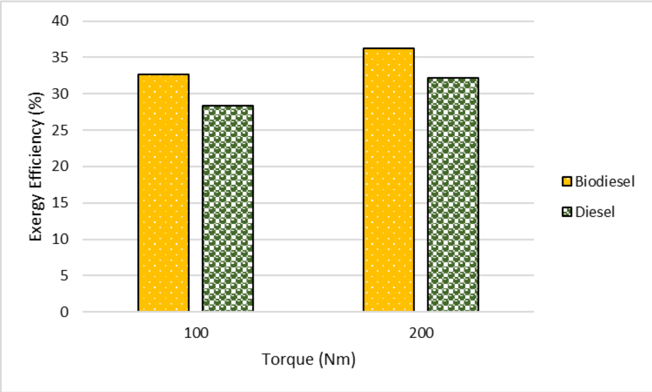


Figure 4.56. Exergy efficiency comparison of the system for DOC+Cordierite

Entropy generation (production) is important in determining the performance of thermal machines such as heat engines, refrigerators, heat pumps, power plants, air conditioners, etc. In addition, it affects the thermodynamics of irreversible processes [25]. The entropy generation rate of the biodiesel fuel is less than the diesel fuel for all engine load and after treatment options. The entropy generation rates of the biodiesel fuel for all systems from maximum to minimum are as follows: Cordierite only>DOC+SiC>DOC+Cordierite>Engine Out>DOC only>SiC only. Also, the entropy generation rates of the diesel fuel for all systems from maximum to minimum are DOC only>DOC+Cordierite>SiC only>cordierite only>DOC+SiC>Engine Out. The entropy generation results of the system for with and without after treatment can be seen in Table 4.13. In addition, the entropy generation comparisons of the system are given in Figure 4.57 through Figure 4.62.

Table 4.13. The entropy generation results of the system for the measured data in the experiment

Entropy Generation (kW/K)		
Engine Out		
	Biodiesel	Diesel
100 Nm	0.0999	0.1220
200Nm	0.1642	0.1981
294 Nm	0.2153	0.2672
DOC only		
100 Nm	0.0991	0.1267
200Nm	0.1710	0.2036
DPF only		
SiC only		
100 Nm	0.0972	0.1254
200 Nm	0.1635	0.2015
Cordierite only		
100 Nm	0.1018	0.1249
200 Nm	0.1710	0.2014
DOC+DPF		
DOC+SiC		
100 Nm	0.1018	0.1236
200 Nm	0.1670	0.2012
DOC+Cordierite		
100 Nm	0.1002	0.1256
200 Nm	0.1672	0.2050

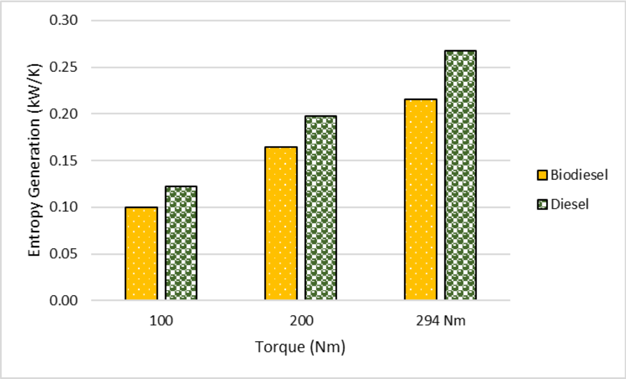


Figure 4.57. Entropy generation comparison of the system for without after treatment

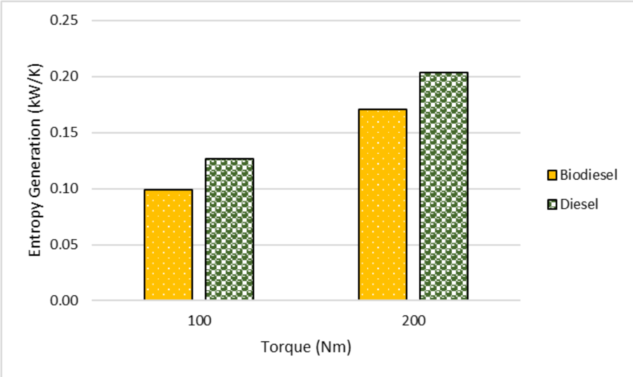


Figure 4.58. Entropy generation comparison of the system for DOC only

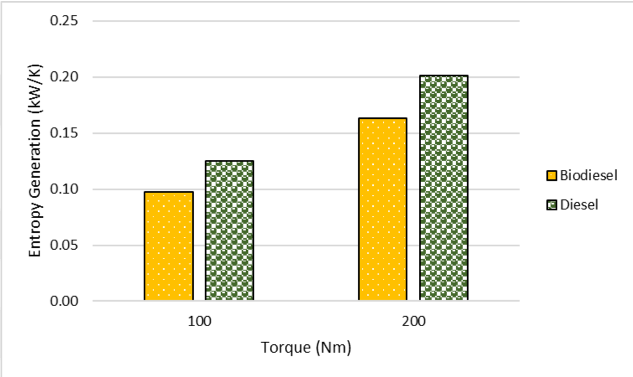


Figure 4.59. Entropy generation comparison of the system for SiC only

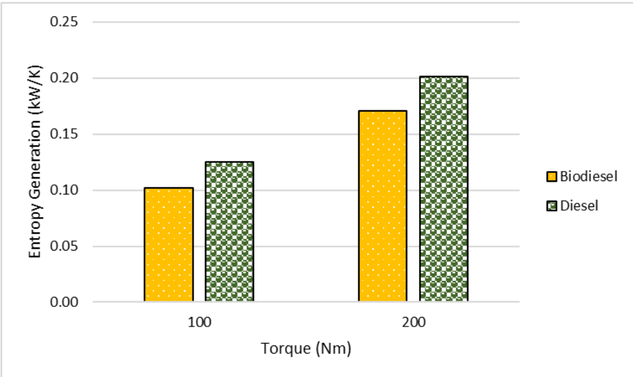


Figure 4.60. Entropy generation comparison of the system for cordierite only

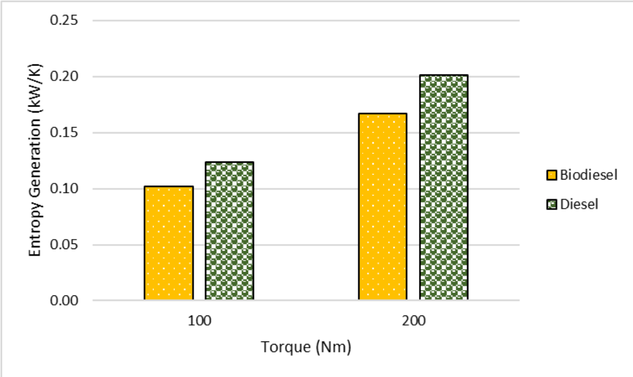


Figure 4.61. Entropy generation comparison of the system for DOC+SiC

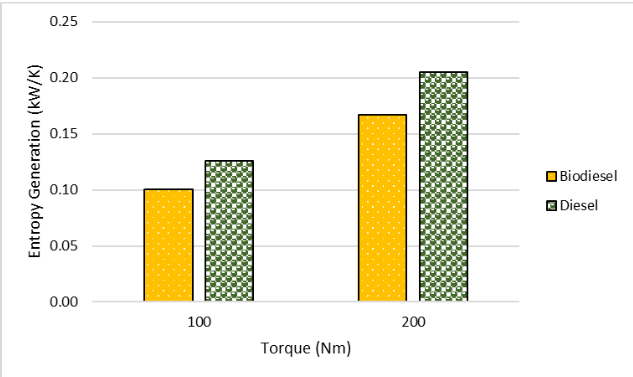


Figure 4.62. Entropy generation comparison of the system for DOC+Cordierite

Environmental analysis has an important role in terms of emission values emitted to the environment. The environmental parameters vary depending on the engine load. If the engine load increases, the environmental parameters increase. Thus, more CO_2 emission is released at higher engine loads. The maximum CO_2 emission releasing in a day is calculated for 294 Nm; while minimum one is found for 100 Nm torque. In addition, enviroeconomic parameter is related with environmental parameter. The enviroeconomic parameter is also related with the carbon emission price. The environmental and enviroeconomic parameters for the biodiesel fuel from maximum to minimum are found as follows: DOC+SiC>DOC+Cordierite>cordierite only>DOC only>Engine Out>SiC only. Also, the environmental and enviroeconomic parameters for the diesel fuel from maximum to minimum are determined to be DOC+Cordierite>DOC only>DOC+SiC>cordierite only>SiC only>Engine Out. The environmental analysis result of the system and the enviroeconomic analysis comparisons of the system for with and without after treatment are shown in Figure 4.63 through Figure 4.74.

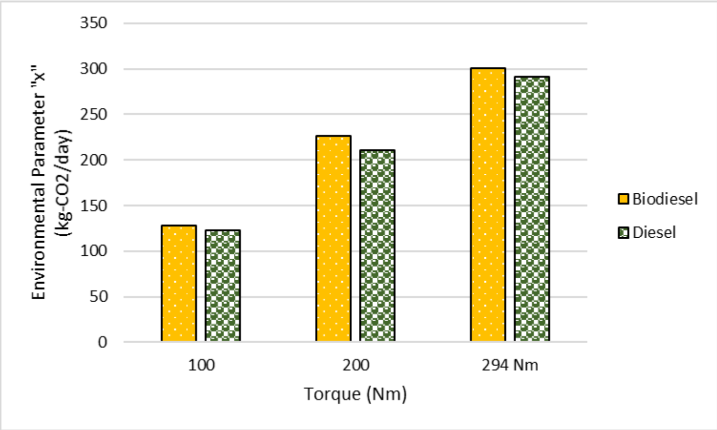


Figure 4.63. Environmental analysis comparison of the system for without after treatment

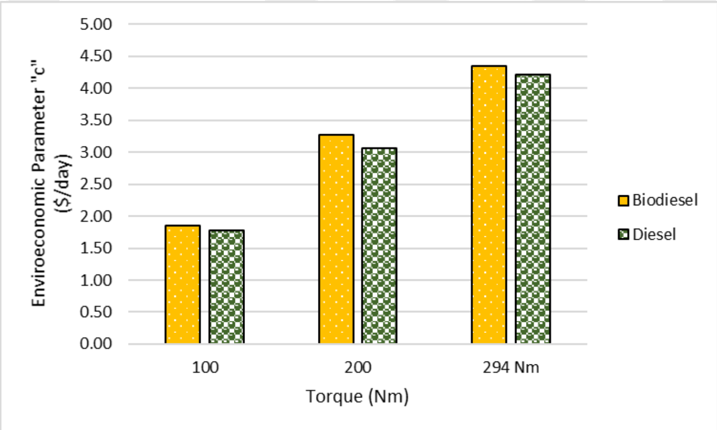


Figure 4.64. Enviroeconomic analysis comparison of the system for without after treatment

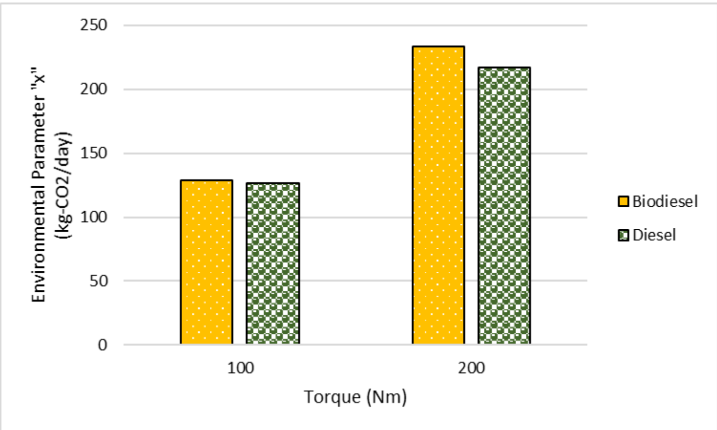


Figure 4.65. Environmental analysis comparison of the system for with DOC only

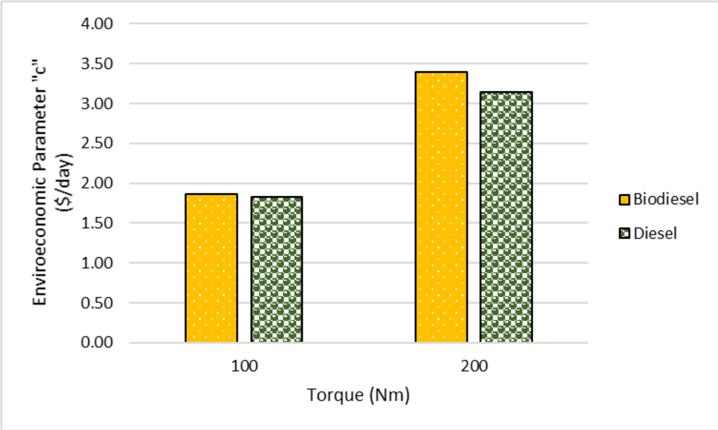


Figure 4.66. Enviroeconomic analysis comparison of the system for DOC only

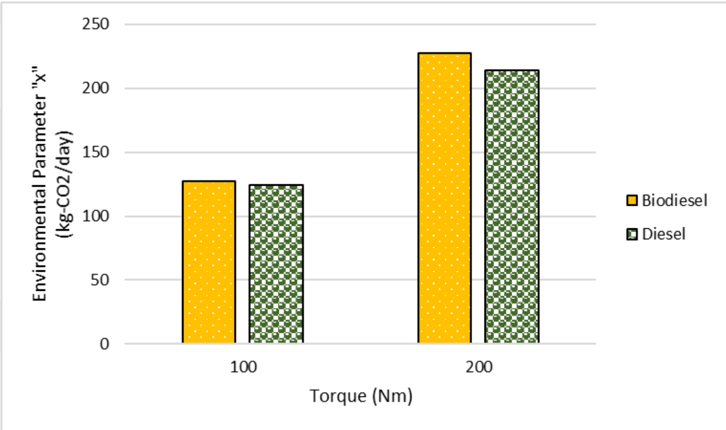


Figure 4.67. Environmental analysis comparison of the system for SiC only

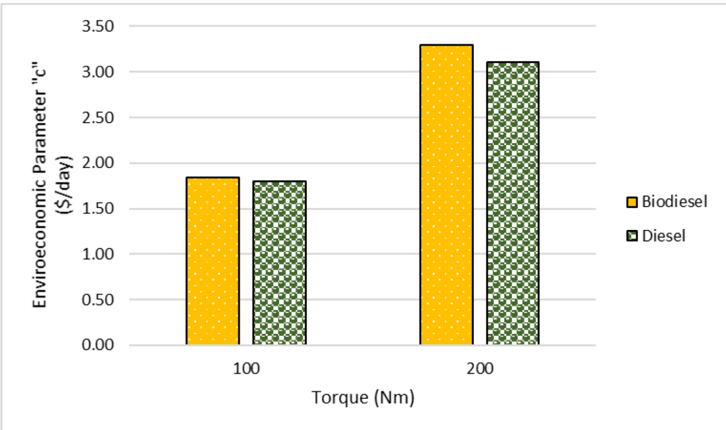


Figure 4.68. Enviroeconomic analysis comparison of the system for SiC only

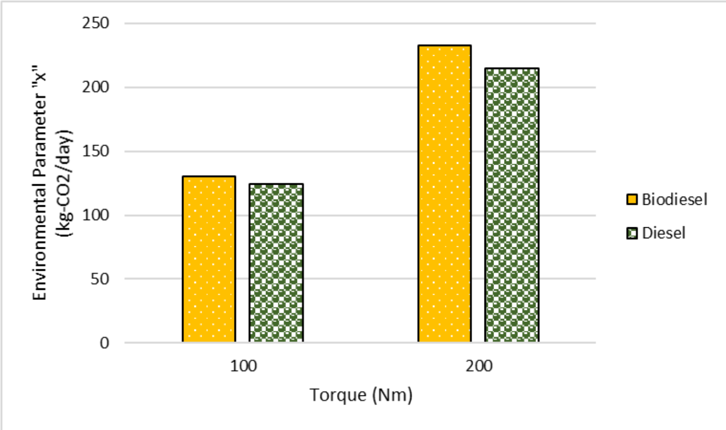


Figure 4.69. Environmental analysis comparison of the system for cordierite only

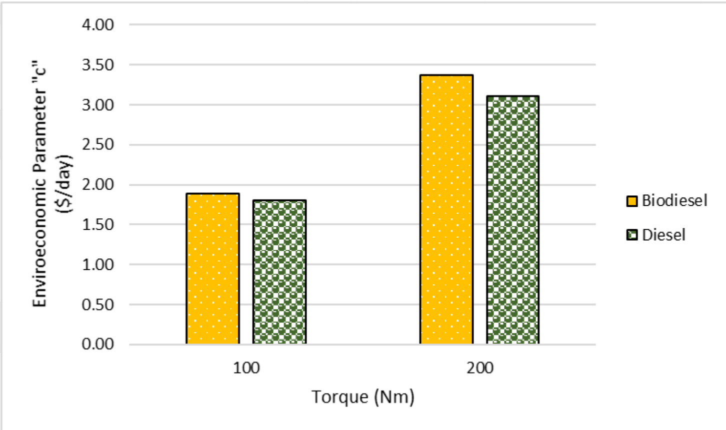


Figure 4.70. Enviroeconomic analysis comparison of the system for cordierite only

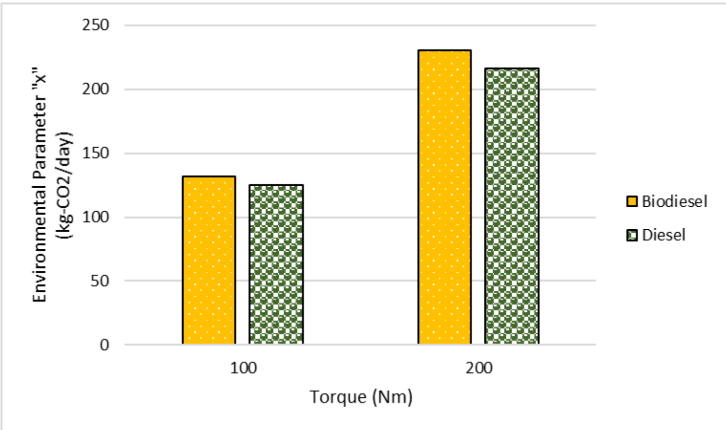


Figure 4.71. Environmental analysis comparison of the system for DOC+SiC

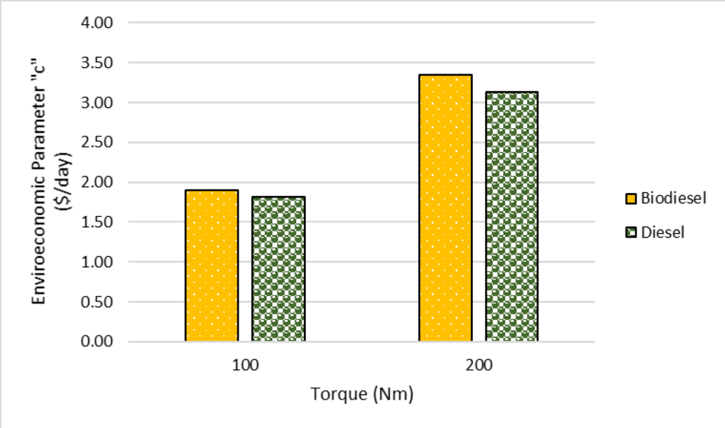


Figure 4.72. Enviroeconomic analysis comparison of the system for DOC+SiC

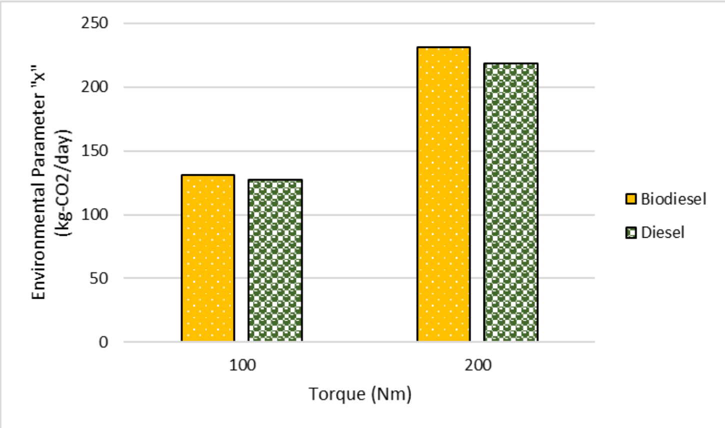


Figure 4.73. Environmental analysis comparison of the system for DOC+Cordierite

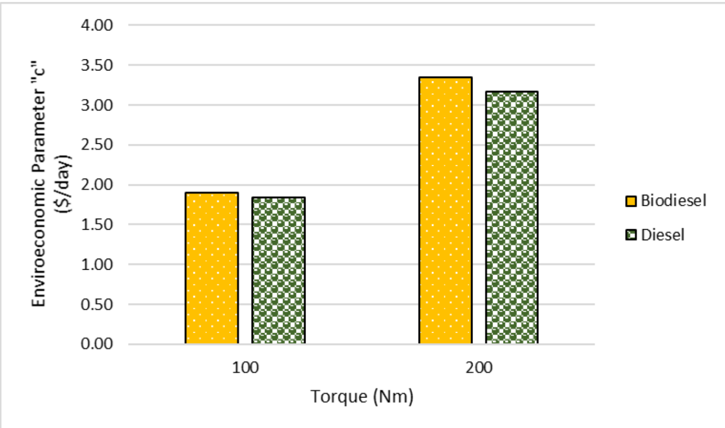


Figure 4.74. Enviroeconomic analysis comparison of the system for DOC+Cordierite

Sustainability index (*SI*) has an important role to determine the sustainable option for the optimization of a system. The *SI* is concerned with the exergy efficiency in order to evaluate the system performance. It is maximum at 294 Nm for without after treatment system, while it is maximum at 200 Nm torque for after treatment system for both of the fuels. Also, it is minimum at 100 Nm torque for both of the fuels and with/without after treatment systems. Therefore, if the engine load is increased, *SI* results also increase. On the other hand, the biodiesel fuel is more sustainable than the diesel fuel. As a consequence, if the biodiesel fuel is used for the engine at 294 Nm for without after treatment and at 200 Nm for after treatment system, the engine is more sustainable. The sustainability analysis comparisons of the system for with and without after treatment are given in Figure 4.75 through Figure 4.80.

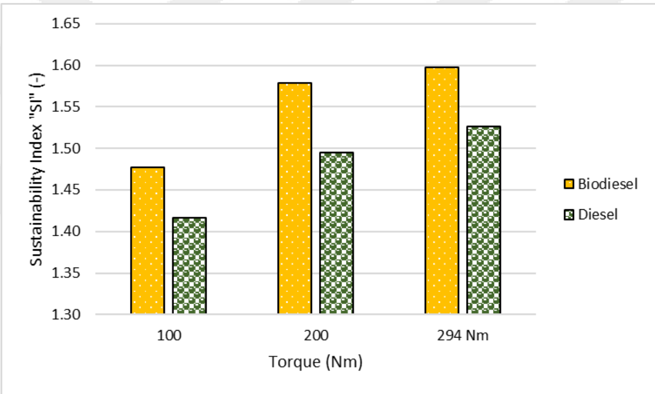


Figure 4.75. Sustainability analysis comparison of the system for without after treatment

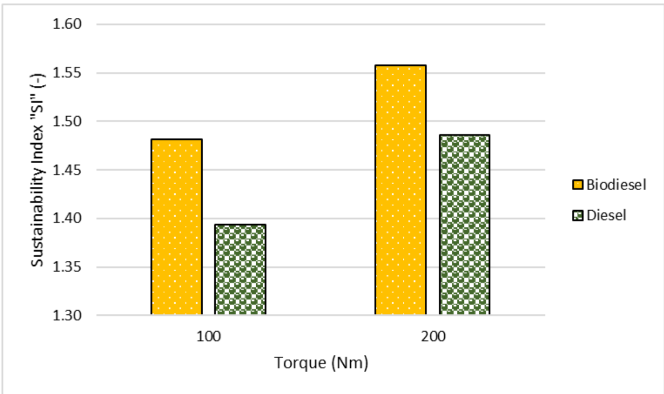


Figure 4.76. Sustainability analysis comparison of the system for DOC only

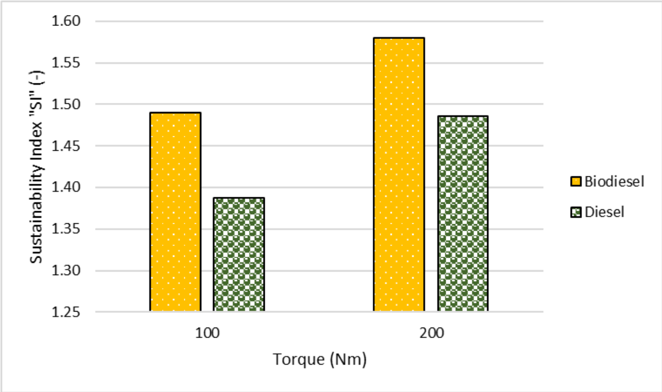


Figure 4.77. Sustainability analysis comparison of the system for SiC only

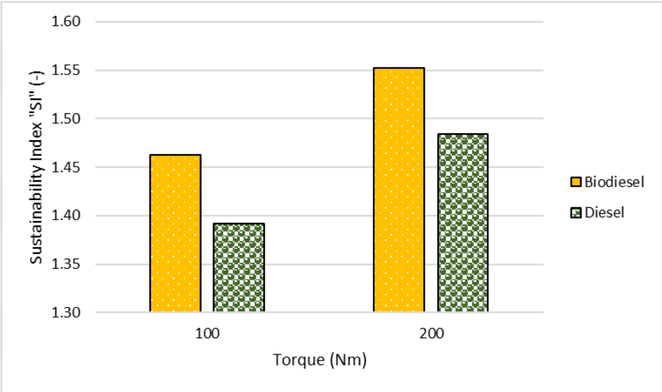


Figure 4.78. Sustainability analysis comparison of the system for cordierite only

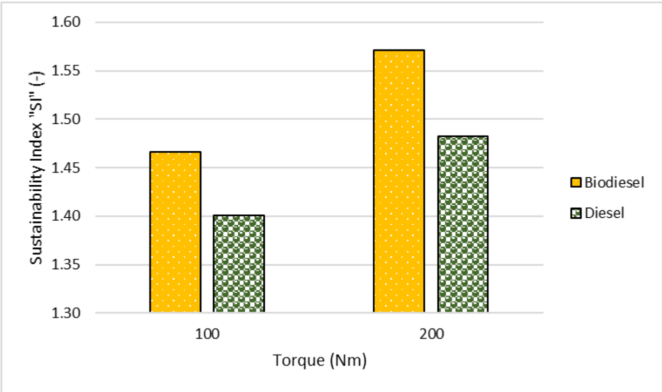


Figure 4.79. Sustainability analysis comparison of the system for DOC+SiC

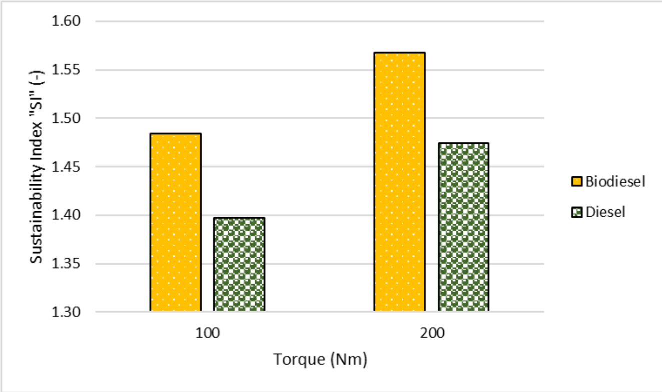


Figure 4.80. Sustainability analysis comparison of the system for DOC+Cordierite

The exergy efficiency and the sustainability index are interrelated. When exergy efficiency increases, the sustainability index also increases. When the rate of exergy efficiency decreases, the sustainability index also decreases. Exergy efficiency and sustainability analysis comparison of the system is shown in Figure 4.81 through Figure 4.86.

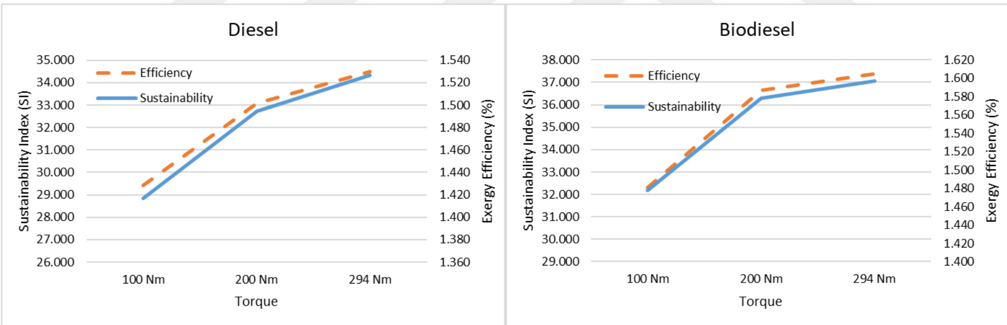


Figure 4.81. Exergy efficiency and sustainability analysis comparison of the system for without after treatment system

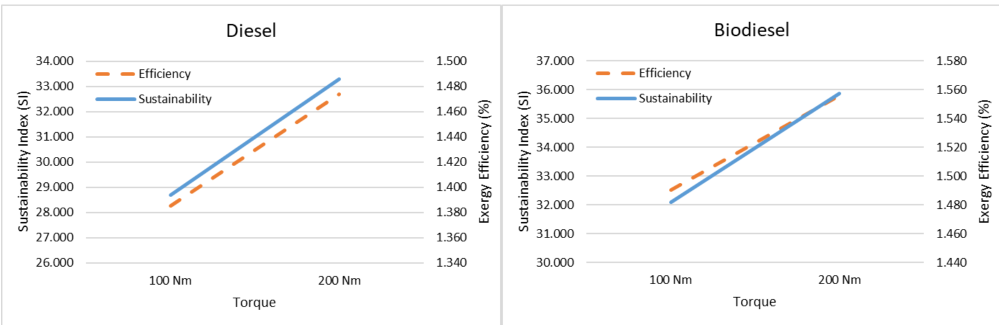


Figure 4.82. Exergy efficiency and sustainability analysis comparison of the system for DOC only

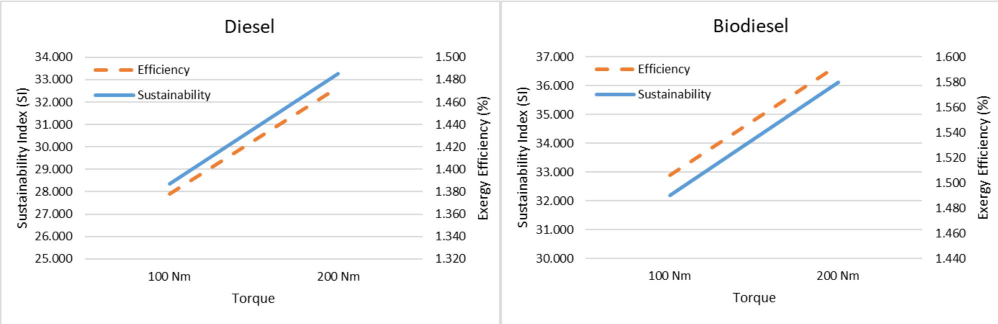


Figure 4.83. Exergy efficiency and sustainability analysis comparison of the system for SiC only

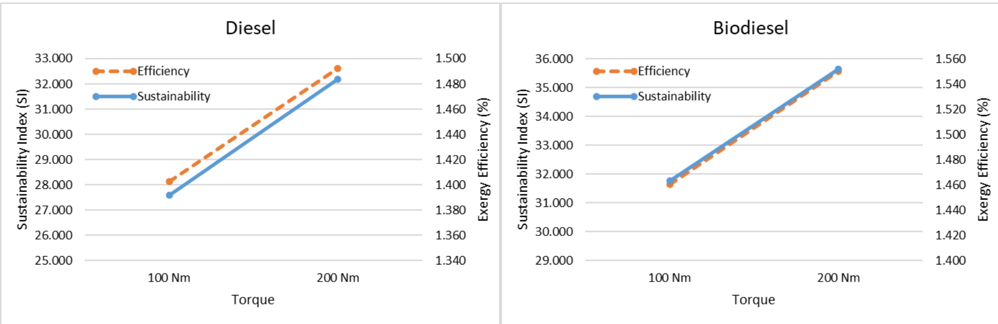


Figure 4.84. Exergy efficiency and sustainability analysis comparison of the system for cordierite only

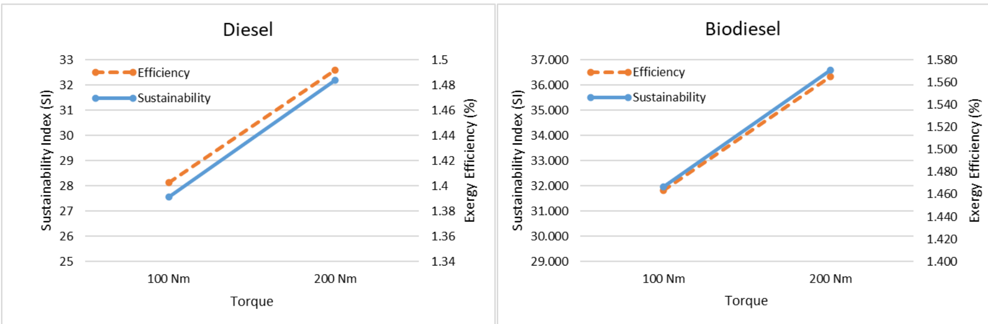


Figure 4.85. Exergy efficiency and sustainability analysis comparison of the system for DOC+SiC

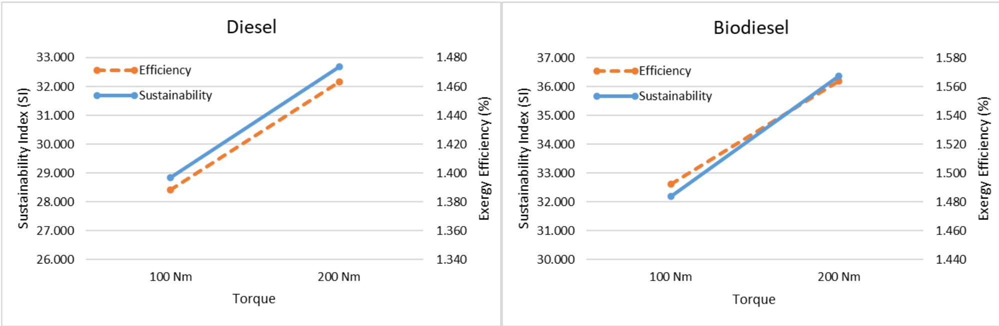


Figure 4.86. Exergy efficiency and sustainability analysis comparison of the system for DOC+Cordierite

The parameter giving information about energy loss per capital cost is called as thermoeconomic parameter. Energy loss is an undesirable part and it can be evaluated by considering the cost of the system in thermoeconomy. Depending on the configuration of the system, energy loss can be minimized by various methods. If the engine load is increased, thermoeconomic parameter also increases and if the engine load is decreased, thermoeconomic parameter also decreases. It is maximum at 294 Nm for without after treatment system, while it is maximum at 200Nm torque for after treatment systems. Also, it is minimum at 100 Nm torque. In addition, the thermoeconomic parameter are calculated to be the biodiesel is less than the diesel at every engine loads. Therefore, the use of biodiesel fuel is a better option for thermoeconomic aspect. If the engine is operated with diesel fuel, the energy loss per capital cost is higher than the biodiesel fuel option. The thermoeconomic analysis comparisons of the system for with and without after treatment are given in Figure 4.87 through Figure 4.92.

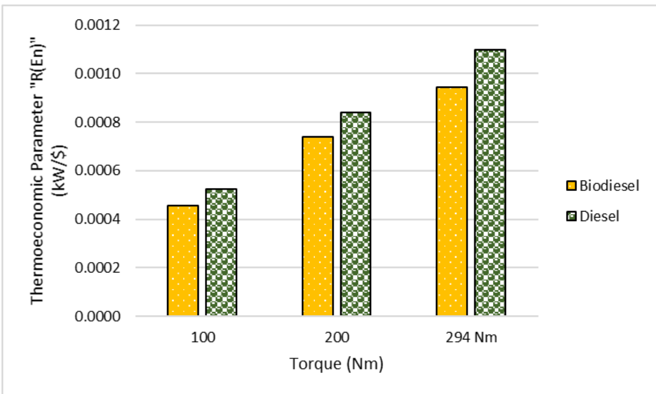


Figure 4.87. Thermoeconomic analysis comparison of the system for without after treatment

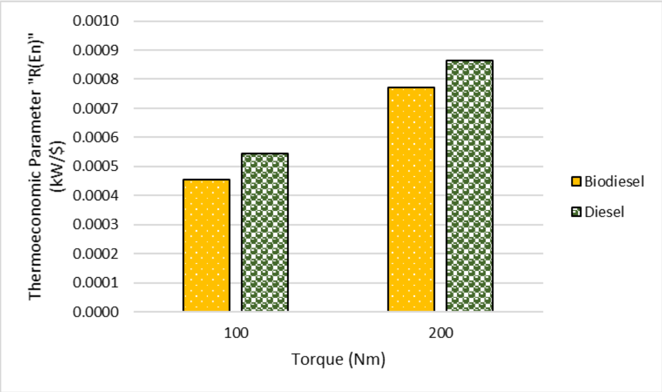


Figure 4.88. Thermoeconomic analysis comparison of the system for DOC only

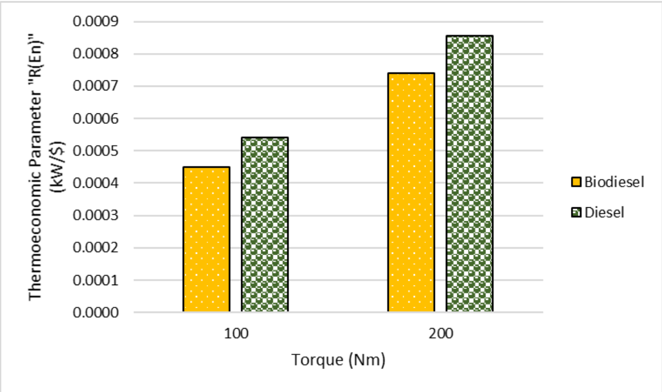


Figure 4.89. Thermoeconomic analysis comparison of the system for SiC only

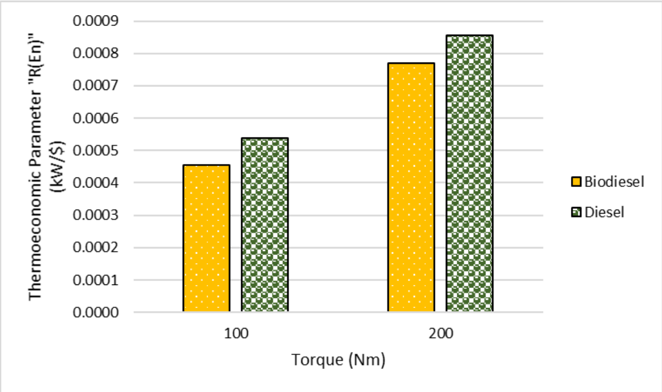


Figure 4.90. Thermoeconomic analysis comparison of the system for cordierite only

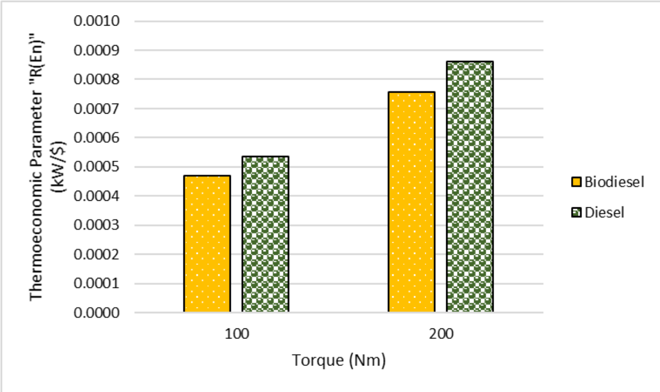


Figure 4.91. Thermoeconomic analysis comparison of the system for DOC+SiC

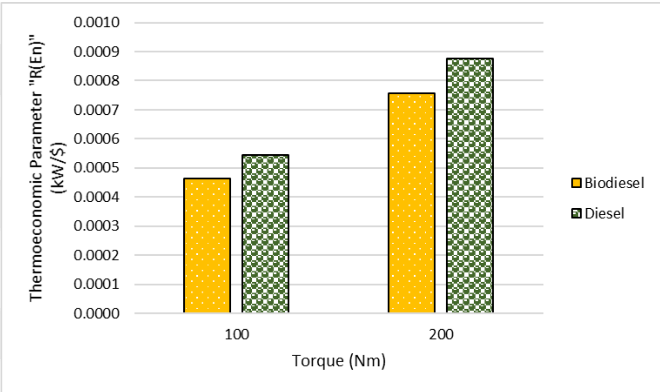


Figure 4.92. Thermoeconomic analysis comparison of the system for DOC+Cordierite

The exergoeconomic parameter is expressed as the sum of exergy loss and destruction per capital cost. The exergy loss can be optimized and it is possible to minimize it. On the other hand, the exergy destruction is referred to as a destructive exergy in the system due to irreversibility [25]. If the engine load is increased, exergoeconomic parameter also increases and if the engine load is decreased, exergoeconomic parameter also decreases. It is maximum at 294 Nm for without after treatment, while it is maximum at 200 Nm torque for after treatment systems. It is also minimum at 100 Nm torque. In addition, the exergoeconomic parameter is calculated as the biodiesel fuel less than the diesel fuel at every engine loads. In this regard, biodiesel fuel is better option compared to diesel fuel for exergoeconomic point of view. The exergoeconomic analysis comparisons of the system for with and without after treatment are given in Figure 4.93 through Figure 4.98.

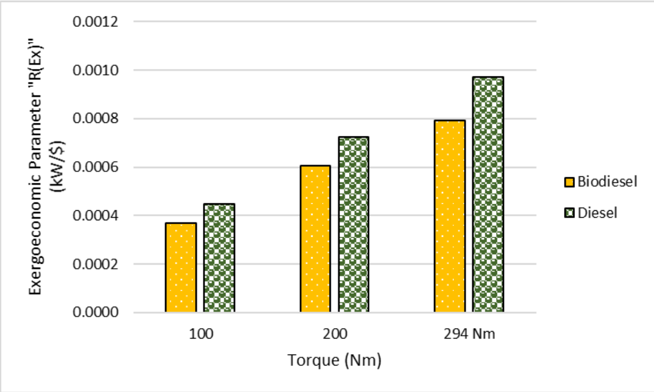


Figure 4.93. Exergoeconomic analysis comparison of the system for without after treatment

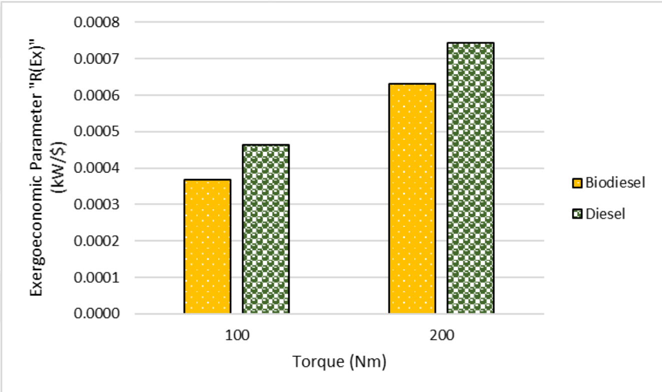


Figure 4.94. Exergoeconomic analysis comparison of the system for DOC only

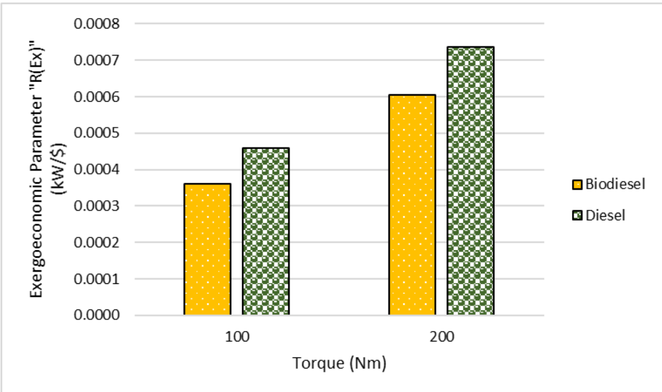


Figure 4.95. Exergoeconomic analysis comparison of the system for SiC only

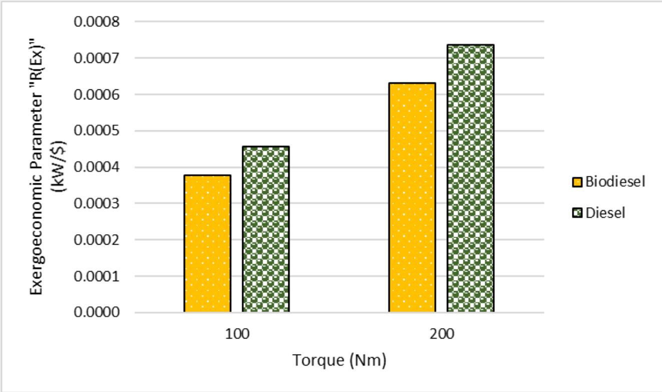


Figure 4.96. Exergoeconomic analysis comparison of the system for cordierite only

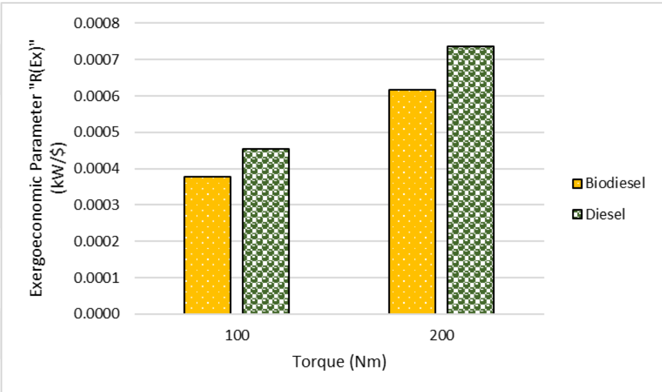


Figure 4.97. Exergoeconomic analysis comparison of the system for DOC+SiC

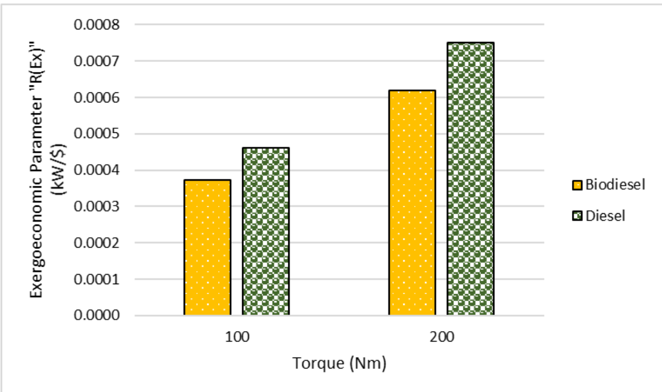


Figure 4.98. Exergoeconomic analysis comparison of the system for DOC+Cordierite

4.3. Comparison of The Results with The Literature

Comparison of this study with the literature is given in Table 4.14. Soltic et al. [16] studied on after treatment systems and achieved an emission particle reduction of 87.0% ~ 98.6% with Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR) after treatment system using EN 590 diesel, Gas-to-liquid (GTL) fuel and Fatty Acid Methyl Ester (FAME) EN 14214 biodiesel. Also, Exhaust Gas Recirculation (EGR) was used to analyze exhaust emissions. Kim et al. [17] calculated 50% smoke emission particle reduction with Catalysed Particulate Filter (CPF) and Warm-up Catalytic Converters (WCC) for Ultra Low Sulphur Diesel (D100), blend of diesel fuel with 15% bioethanol (E15), blend of diesel fuel with 15% bioethanol and cetane improver (E15CI) and mixed fuel of biodiesel and bioethanol (BD15E5), BD05, BD20 biodiesel fuels at 1500 rpm and 2500 rpm engine speed. The Condensation Particle Counter (CPC) and Scanning Mobility Particle Sizer (SMPS) are used for emission analyzers. Rounce et al. [18] determined 99% and 96% emission particle reduction for solid and liquid particulate matter, respectively. Ultra Low Sulphur Diesel (ULSD) and Rapeseed methyl ester (RME) biodiesel fuels were tested. The particles were measured by using EGR and SMPS for DOC and DPF after treatment systems, while the engine speed was 1500 rpm. Oravisjärvi et al. [21] obtained about 99% emission particle reduction in diesel engine by using DPF and SCR for Summer grade and ULSD diesel fuels, while the engine speed was 2200 rpm and the Electrical Low Pressure Impactor (ELPI) was used as particle analyzer. Feng et al. [22] studied on effect of Particulate Oxidation Catalyst (POC) for diesel fuel at 1200 rpm engine speed. In order to measure the emission values, Engine Exhaust Particle Sizer (EEPS) was used and it was found that the POC reduces 61% of the emissions. Huang et al. [23] used DOC and DPF after treatment systems in the diesel engine and found 7% and 27% emission particle reduction rates for Swedish diesel fuel, and 68% and 81% emission particle reduction rates for B100 biodiesel fuel at 1500 rpm and 2500 rpm, respectively. Mori et al. [10] used EEPS particle sizer and tested BDF20, BDF50, BDF100 biodiesel and JIS#3 diesel fuel with DPF after treatment system in the diesel engine. It was seen that about 99.95% of the emission particles released to the environment was removed. Wei et al. [24] studied the effect of the DOC and DPOC (DOC coupled with particulate oxidation catalyst) after treatment systems on methanol and sulphur contented diesel fuels. It was calculated that ~89% and

~99.37% emission particle reductions were achieved at 1660 rpm, and 2090 rpm engine speeds, while the Horiba MEXA-6000FT Exhaust Gas Analyzer was used. Zhang et al. [26] worked on the diesel fuel emission particle reduction by using DOC, Catalytic Diesel Particulate Filter (CDPF) and SCR after treatment systems, while the EEPS was used as emission particle sizer. It was found that DOC reduced 63.4% of the particles, while the CDPF reduced 98.6% at 2300 rpm engine speed. In present study, the diesel engine is loaded with 100 Nm, 200 Nm and 294 Nm for without after treatment, while it is loaded at 100 Nm and 200 Nm for various after treatment systems. BDF100 biodiesel and JIS#2 diesel fuels are tested in this system. Also, DOC and two different types of DPFs are used as after treatment systems. DPF has two materials as silicon carbide (SiC) and cordierite diesel particulate filter. The particle sizes and total particle concentrations are measured with SMPS. When DOC is used with SiC diesel particulate filter, 99.97% of the exhaust emission particles can be prevented. In addition, if the DOC is used with cordierite DPF, the exhaust emission particle reduction rate is 98.57%. Although there is little difference between SiC and cordierite, the SiC diesel particulate filter prevents more emission particles than cordierite DPF.

Table 4.14. Comparison of this study with the literature

No	Author(s)	Year	Fuel	Exhaust Gas & Particle Size Analyzer	After Treatment System	Torque/rpm	Emission Particle Reduction	Maximum & Minimum Particle Size
1	Soltic et. al.	2009	➢ EN 590 diesel ➢ Gas-To-Liquid (GTL) fuel ➢ Fatty Acid Methyl Ester (FAME) EN 14214 biodiesel	➢ Exhaust Gas Recirculation (EGR)	➢ Diesel Oxidation Catalyst (DOC) ➢ Diesel Particulate Filter (DPF) ➢ Selective Catalytic Reduction (SCR)	-	87.0% ~ 98.6%	-
2	Kim et. al.	2010	➢ Ultra Low Sulphur Diesel (D100) ➢ Blend of diesel fuel with 15% (by vol.) bioethanol (E15) ➢ Blend of diesel fuel with 15% bioethanol and cetane improver (E15CI) ➢ Mixed fuel of biodiesel and bioethanol (BD15E5) ➢ BD05, BD20 biodiesel	➢ Condensation Particle Counter (CPC) ➢ Scanning Mobility Particle Sizer (SMPS)	➢ Catalysed Particulate Filter (CPF) ➢ Warm-up catalytic converters (WCC)	2100 rpm 3800 rpm	50% (Smoke) 97%(Particle mass)	Max: ~385 nm* Min: ~50 nm*
3	Rounce et. al.	2012	➢ Ultra Low Sulphur Diesel (ULSD) ➢ Rapeseed methyl ester (RME) biodiesel	➢ EGR ➢ SMPS	➢ DOC ➢ DPF	1500 rpm	~99% (Solid PM) ~96% (Liquid PM)	Max: ~ 500 nm* Min: ~10 nm*

*Calculated by the author

Table 4.14. Comparison of this study with the literature (Continued)

No	Author(s)	Year	Fuel	Exhaust Gas & Particle Size Analyzer	After Treatment System	Torque/rpm	Emission Particle Reduction	Maximum & Minimum Particle Size
4	Oravisjärvi et. al.	2014	➢ Summer grade diesel ➢ ULSD	➢ Electrical Low Pressure Impactor (ELPI)	➢ Diesel Particulate Filter (DPF) ➢ Selective Catalytic Reduction (SCR)	2200 rpm	~ 99%	-
5	Feng et. al.	2014	➢ Diesel	➢ Engine Exhaust Particle Sizer (EEPS)	➢ Particulate Oxidation Catalyst (POC)	1200 rpm	61%	Max: ~220.7 nm* Min: ~6.04 nm*
6	Huang et. al.	2015	➢ ULSD ➢ Swedish diesel ➢ Low Aromatic Diesel ➢ Neat Soy-Based Biodiesel (B100)	➢ EGR	➢ DOC ➢ DPF	1500 rpm	7% (Swedish) 68% (B100)	-
						2500 rpm	27% (Swedish) 81% (B100)	
7	Mori et. al.	2015	➢ BDF20, BDF50, BDF100 biodiesel ➢ JIS#3 diesel	➢ EEPS	➢ DPF	200 Nm	over 99.95%	Max: ~560 nm* Min: ~5.6 nm*

*Calculated by the author

Table 4.14. Comparison of this study with the literature (Continued)

No	Author(s)	Year	Fuel	Exhaust Gas & Particle Size Analyzer	After Treatment System	Torque/rpm	Emission Particle Reduction	Maximum & Minimum Particle Size
8	Wei et. al.	2017	➢ Methanol ➢ Diesel (Sulphur contents)	➢ Horiba MEXA-6000FT Exhaust Gas Analyzer	➢ DOC ➢ DOC coupled with particulate oxidation catalyst (DPOC)	1660 rpm	~ 89%*	-
						2090 rpm	~ 99.37%*	
9	Zhang et. al.	2018	➢ Diesel	➢ EEPS	➢ DOC ➢ Catalytic Diesel Particulate Filter (CDPF) ➢ SCR	2300 rpm	63.4% (DOC) 98.6% (CDPF)	Max: ~560 nm* Min: ~5.6 nm*
10	Present study	2018	➢ BDF100 biodiesel ➢ JIS#2 diesel	➢ SMPS	➢ DOC ➢ DPF (Silicon Carbide/SiC) ➢ DPF (Cordierite)	100 Nm	99.97% (DOC+SiC) 98.57% (DOC+Cordierite)	Max: 162.5 nm Min: 4.61 nm
						200 Nm		

*Calculated by the author

4.4. Error Analysis Results

Each fuel is tested five times for with and without after treatment system. So, it is necessary to apply error analysis. The error analysis is applied to the experimental measurement/test results. According to error analysis, the standard deviation, maximum relative error and minimum relative error values are determined for measurement/test results of with and without after treatment systems. The average values are used in the analyses of the systems. As a result of error analysis, the maximum relative error of the system is found as 33.18% (for $\dot{m}_{HC}$ at 100 Nm) for the diesel fuel tested with cordierite only after treatment system, while the minimum relative error is zero (0%). The error analysis results for with and without after treatment systems are illustrated in Table 4.15 through Table 4.27.

Table 4.15. Error analysis results of the biodiesel fuel for without after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
Engine Out												
Biodiesel (100 Nm)												
1	99.05	1.369 10^{-6}	31.687 10^{-3}	24.90	26.51	80.00	295.00	27.993 10^{-3}	3.3974 10^{-6}	0.3305 10^{-6}	15.6790 10^{-6}	4292.3130 10^{-6}
2	99.05	1.442 10^{-6}	33.393 10^{-3}	24.80	27.94	80.00	295.00	27.993 10^{-3}	3.5961 10^{-6}	0.3421 10^{-6}	16.6980 10^{-6}	4543.4083 10^{-6}
3	97.09	1.405 10^{-6}	32.633 10^{-3}	24.90	27.31	80.00	294.00	27.993 10^{-3}	3.5141 10^{-6}	0.3373 10^{-6}	16.1425 10^{-6}	4425.5971 10^{-6}
4	98.07	1.422 10^{-6}	32.919 10^{-3}	24.90	27.55	80.00	294.00	27.993 10^{-3}	3.5146 10^{-6}	0.3146 10^{-6}	16.5617 10^{-6}	4479.0094 10^{-6}
5	98.07	1.435 10^{-6}	33.334 10^{-3}	25.00	27.90	80.00	293.00	27.993 10^{-3}	3.6201 10^{-6}	0.3093 10^{-6}	16.7673 10^{-6}	4520.0884 10^{-6}
Average	98.26	1.415 10^{-6}	32.793 10^{-3}	24.90	27.44	80.00	294.20	27.993 10^{-3}	3.5285 10^{-6}	0.3268 10^{-6}	16.3697 10^{-6}	4452.0832 10^{-6}
Standard Deviation	0.37	0.013 10^{-6}	0.310 10^{-3}	0.03	0.26	0.00	0.37	0.000 10^{-3}	0.0391 10^{-6}	0.0064 10^{-6}	0.2039 10^{-6}	44.6755 10^{-6}
Maximum Relative Error (%)	1.19	3.36	3.49	0.40	3.51	0.00	0.41	0.00	3.86	5.28	4.41	3.72
Minimum Relative Error (%)	0.20	0.52	0.40	0.00	0.42	0.00	0.07	0.00	0.41	1.12	1.22	0.62
Biodiesel (200 Nm)												
1	197.11	2.555 10^{-6}	54.547 10^{-3}	25.20	45.69	80.00	328.00	57.319 10^{-3}	3.0761 10^{-6}	0.2845 10^{-6}	43.1267 10^{-6}	8053.1667 10^{-6}
2	197.11	2.574 10^{-6}	54.732 10^{-3}	25.40	45.85	80.00	320.00	57.319 10^{-3}	3.0841 10^{-6}	0.2627 10^{-6}	43.8533 10^{-6}	8105.6278 10^{-6}
3	195.15	2.547 10^{-6}	54.209 10^{-3}	25.40	45.42	80.00	319.00	57.319 10^{-3}	2.9052 10^{-6}	0.2504 10^{-6}	43.6275 10^{-6}	8022.4959 10^{-6}
4	197.11	2.269 10^{-6}	48.483 10^{-3}	25.40	40.62	80.00	319.00	57.319 10^{-3}	2.6434 10^{-6}	0.2151 10^{-6}	38.9207 10^{-6}	7147.8662 10^{-6}
5	195.15	2.518 10^{-6}	53.697 10^{-3}	25.40	45.00	80.00	319.00	57.319 10^{-3}	3.0771 10^{-6}	0.2309 10^{-6}	42.9193 10^{-6}	7933.5951 10^{-6}
Average	196.33	2.492 10^{-6}	53.134 10^{-3}	25.36	44.52	80.00	321.00	57.319 10^{-3}	2.9572 10^{-6}	0.2487 10^{-6}	42.4895 10^{-6}	7852.5503 10^{-6}
Standard Deviation	0.48	0.057 10^{-6}	1.176 10^{-3}	0.04	0.98	0.00	1.76	0.000 10^{-3}	0.0854 10^{-6}	0.0121 10^{-6}	0.9078 10^{-6}	178.3710 10^{-6}
Maximum Relative Error (%)	0.60	8.96	8.75	0.63	8.75	0.00	2.18	0.00	10.61	14.39	8.40	8.97
Minimum Relative Error (%)	0.40	1.02	1.06	0.16	1.09	0.00	0.31	0.00	1.76	0.67	1.01	1.03

Table 4.16. Error analysis results of the diesel fuel for without after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
Engine Out												
Diesel (100 Nm)												
1	101.99	1.416 10^{-6}	32.931 10^{-3}	24.60	27.51	80.00	304.00	29.326 10^{-3}	4.1686 10^{-6}	0.4803 10^{-6}	15.4955 10^{-6}	4435.6275 10^{-6}
2	102.97	1.360 10^{-6}	31.530 10^{-3}	24.60	26.34	80.00	304.00	30.659 10^{-3}	4.0365 10^{-6}	0.5066 10^{-6}	14.8588 10^{-6}	4277.6003 10^{-6}
3	102.97	1.280 10^{-6}	29.654 10^{-3}	24.70	24.77	80.00	305.00	29.326 10^{-3}	3.7950 10^{-6}	0.4954 10^{-6}	14.2053 10^{-6}	4026.0527 10^{-6}
4	102.97	1.363 10^{-6}	31.636 10^{-3}	24.70	26.44	80.10	304.00	29.326 10^{-3}	4.0799 10^{-6}	0.5505 10^{-6}	15.1136 10^{-6}	4287.9073 10^{-6}
5	101.99	1.372 10^{-6}	31.723 10^{-3}	24.80	26.52	80.00	305.00	30.659 10^{-3}	4.0306 10^{-6}	0.5576 10^{-6}	15.2199 10^{-6}	4316.3781 10^{-6}
Average	102.58	1.358 10^{-6}	31.495 10^{-3}	24.68	26.32	80.02	304.40	29.859 10^{-3}	4.0221 10^{-6}	0.5181 10^{-6}	14.9786 10^{-6}	4268.7132 10^{-6}
Standard Deviation	0.24	0.022 10^{-6}	0.526 10^{-3}	0.04	0.44	0.02	0.24	0.327 10^{-3}	0.0619 10^{-6}	0.0153 10^{-6}	0.2186 10^{-6}	66.8819 10^{-6}
Maximum Relative Error (%)	0.58	5.51	5.59	0.49	5.60	0.10	0.20	2.73	5.45	8.23	4.99	5.47
Minimum Relative Error (%)	0.38	0.11	0.11	0.08	0.09	0.03	0.13	1.82	0.20	2.39	0.77	0.20
Diesel (200 Nm)												
1	198.09	2.406 10^{-6}	51.442 10^{-3}	25.30	43.04	80.00	333.00	57.319 10^{-3}	3.9415 10^{-6}	0.6604 10^{-6}	37.1826 10^{-6}	7568.6527 10^{-6}
2	198.09	2.357 10^{-6}	50.343 10^{-3}	25.30	42.12	80.00	332.00	57.319 10^{-3}	3.9035 10^{-6}	0.6600 10^{-6}	36.9179 10^{-6}	7413.7997 10^{-6}
3	197.11	2.287 10^{-6}	48.804 10^{-3}	25.20	40.84	80.00	332.00	57.319 10^{-3}	3.7860 10^{-6}	0.6624 10^{-6}	35.0912 10^{-6}	7197.6966 10^{-6}
4	198.09	2.233 10^{-6}	47.607 10^{-3}	25.30	39.84	80.00	332.00	57.319 10^{-3}	3.6478 10^{-6}	0.6634 10^{-6}	34.7198 10^{-6}	7025.4000 10^{-6}
5	198.09	2.360 10^{-6}	50.262 10^{-3}	25.30	42.06	80.00	333.00	57.319 10^{-3}	3.7586 10^{-6}	0.6866 10^{-6}	36.6086 10^{-6}	7424.6580 10^{-6}
Average	197.90	2.329 10^{-6}	49.692 10^{-3}	25.28	41.58	80.00	332.40	57.319 10^{-3}	3.8075 10^{-6}	0.6666 10^{-6}	36.1040 10^{-6}	7326.0414 10^{-6}
Standard Deviation	0.20	0.031 10^{-6}	0.669 10^{-3}	0.02	0.56	0.00	0.24	0.000 10^{-3}	0.0527 10^{-6}	0.0050 10^{-6}	0.5011 10^{-6}	95.6934 10^{-6}
Maximum Relative Error (%)	0.40	4.10	4.20	0.32	4.19	0.00	0.18	0.00	4.19	3.01	3.83	4.10
Minimum Relative Error (%)	0.10	1.22	1.15	0.08	1.16	0.00	0.12	0.00	0.56	0.48	1.40	1.20

Table 4.17. Error analysis results of the fuels for without after treatment system at 294 Nm

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
Engine Out												
Biodiesel (294 Nm)												
1	267.72	3.269 10^{-6}	63.326 10^{-3}	25.50	53.07	80.00	365.00	66.650 10^{-3}	2.2118 10^{-6}	0.2304 10^{-6}	84.8776 10^{-6}	10296.6100 10^{-6}
2	266.74	3.361 10^{-6}	64.887 10^{-3}	25.50	54.40	80.10	365.00	66.650 10^{-3}	2.2667 10^{-6}	0.2332 10^{-6}	88.4526 10^{-6}	10589.3722 10^{-6}
3	265.76	3.301 10^{-6}	63.730 10^{-3}	25.60	53.43	80.00	365.00	66.650 10^{-3}	2.2843 10^{-6}	0.2232 10^{-6}	86.3404 10^{-6}	10397.8317 10^{-6}
4	265.76	3.355 10^{-6}	64.718 10^{-3}	25.70	54.26	80.00	365.00	66.650 10^{-3}	2.3186 10^{-6}	0.2265 10^{-6}	87.7684 10^{-6}	10563.5113 10^{-6}
5	264.78	3.276 10^{-6}	63.246 10^{-3}	25.70	53.02	80.00	364.00	66.650 10^{-3}	2.2660 10^{-6}	0.2271 10^{-6}	84.9173 10^{-6}	10314.6303 10^{-6}
Average	266.15	3.312 10^{-6}	63.981 10^{-3}	25.60	53.64	80.02	364.80	66.650 10^{-3}	2.2695 10^{-6}	0.2281 10^{-6}	86.4713 10^{-6}	10432.3911 10^{-6}
Standard Deviation	0.50	0.019 10^{-6}	0.346 10^{-3}	0.04	0.29	0.02	0.20	0.000 10^{-3}	0.0173 10^{-6}	0.0017 10^{-6}	0.7273 10^{-6}	61.3735 10^{-6}
Maximum Relative Error (%)	0.59	1.46	1.42	0.39	1.42	0.10	0.22	0.00	2.54	2.23	2.29	1.50
Minimum Relative Error (%)	0.15	0.34	0.39	0.00	0.38	0.02	0.05	0.00	0.12	0.42	0.15	0.33
Biodiesel (294 Nm)												
1	284.39	3.183 10^{-6}	60.767 10^{-3}	25.30	50.87	80.00	392.00	70.649 10^{-3}	3.1794 10^{-6}	0.7481 10^{-6}	79.6310 10^{-6}	10015.6039 10^{-6}
2	284.39	3.229 10^{-6}	61.356 10^{-3}	25.50	51.38	80.00	393.00	70.649 10^{-3}	3.1517 10^{-6}	0.8300 10^{-6}	80.1952 10^{-6}	10158.4760 10^{-6}
3	284.39	3.192 10^{-6}	60.698 10^{-3}	25.60	50.83	80.00	393.00	69.316 10^{-3}	3.3399 10^{-6}	0.8126 10^{-6}	80.1046 10^{-6}	10038.6532 10^{-6}
4	284.39	3.182 10^{-6}	60.443 10^{-3}	25.50	50.62	80.20	393.00	70.649 10^{-3}	3.3268 10^{-6}	0.8287 10^{-6}	80.1534 10^{-6}	10008.0425 10^{-6}
5	284.39	3.264 10^{-6}	61.969 10^{-3}	25.50	51.90	80.20	393.00	70.649 10^{-3}	3.2972 10^{-6}	0.8243 10^{-6}	82.3328 10^{-6}	10269.7776 10^{-6}
Average	284.39	3.210 10^{-6}	61.047 10^{-3}	25.48	51.12	80.08	392.80	70.382 10^{-3}	3.2590 10^{-6}	0.8087 10^{-6}	80.4834 10^{-6}	10098.1106 10^{-6}
Standard Deviation	0.00	0.016 10^{-6}	0.275 10^{-3}	0.05	0.23	0.05	0.20	0.267 10^{-3}	0.0390 10^{-6}	0.0155 10^{-6}	0.4734 10^{-6}	50.7781 10^{-6}
Maximum Relative Error (%)	0.00	1.69	1.51	0.71	1.52	0.15	0.20	1.52	3.29	7.50	2.30	1.70
Minimum Relative Error (%)	0.00	0.55	0.46	0.08	0.49	0.10	0.05	0.38	1.17	0.48	0.36	0.60

Table 4.18. Error analysis results of the biodiesel fuel for DOC only after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DOC only												
Biodiesel (100 Nm)												
1	97.09	1.372 10^{-6}	32.067 10^{-3}	25.90	26.79	80.00	290.00	18.662 10^{-3}	0.0298 10^{-6}	0.0546 10^{-6}	7.2240 10^{-6}	4332.8672 10^{-6}
2	99.05	1.428 10^{-6}	33.354 10^{-3}	25.90	27.86	80.00	289.00	19.995 10^{-3}	0.0311 10^{-6}	0.0570 10^{-6}	7.7053 10^{-6}	4530.7456 10^{-6}
3	98.07	1.408 10^{-6}	32.838 10^{-3}	26.00	27.43	80.00	289.00	18.662 10^{-3}	0.0307 10^{-6}	0.0546 10^{-6}	7.7469 10^{-6}	4464.1655 10^{-6}
4	98.07	1.393 10^{-6}	32.671 10^{-3}	26.00	27.30	80.00	287.00	19.995 10^{-3}	0.0305 10^{-6}	0.0544 10^{-6}	7.8722 10^{-6}	4418.9252 10^{-6}
5	100.03	1.447 10^{-6}	33.728 10^{-3}	26.00	28.19	80.00	289.00	19.995 10^{-3}	0.0315 10^{-6}	0.0577 10^{-6}	8.2281 10^{-6}	4591.4319 10^{-6}
Average	98.46	1.410 10^{-6}	32.932 10^{-3}	25.96	27.51	80.00	288.80	19.462 10^{-3}	0.0307 10^{-6}	0.0557 10^{-6}	7.7553 10^{-6}	4467.6271 10^{-6}
Standard Deviation	0.50	0.013 10^{-6}	0.286 10^{-3}	0.02	0.24	0.00	0.49	0.327 10^{-3}	0.0003 10^{-6}	0.0007 10^{-6}	0.1616 10^{-6}	44.6406 10^{-6}
Maximum Relative Error (%)	1.62	2.76	2.70	0.23	2.71	0.00	0.62	4.29	3.04	3.69	7.35	3.11
Minimum Relative Error (%)	0.40	0.15	0.29	0.15	0.30	0.00	0.07	2.86	0.23	1.90	0.12	0.08
Biodiesel (200 Nm)												
1	197.11	2.630 10^{-6}	56.550 10^{-3}	26.30	47.28	80.30	314.00	43.989 10^{-3}	0.0526 10^{-6}	0.0963 10^{-6}	22.0079 10^{-6}	8337.4793 10^{-6}
2	198.09	2.594 10^{-6}	55.826 10^{-3}	26.30	46.67	80.10	313.00	41.323 10^{-3}	0.0519 10^{-6}	0.0745 10^{-6}	22.5754 10^{-6}	8221.9202 10^{-6}
3	198.09	2.589 10^{-6}	55.624 10^{-3}	26.10	46.49	80.00	313.00	43.989 10^{-3}	0.0517 10^{-6}	0.0742 10^{-6}	22.5755 10^{-6}	8212.4269 10^{-6}
4	196.13	2.534 10^{-6}	54.279 10^{-3}	26.20	45.37	80.00	313.00	43.989 10^{-3}	0.0505 10^{-6}	0.0699 10^{-6}	22.2101 10^{-6}	8034.2629 10^{-6}
5	195.15	2.458 10^{-6}	52.747 10^{-3}	26.20	44.09	80.00	313.00	43.456 10^{-3}	0.0490 10^{-6}	0.0704 10^{-6}	20.6651 10^{-6}	7792.9557 10^{-6}
Average	196.92	2.561 10^{-6}	55.005 10^{-3}	26.22	45.98	80.08	313.20	43.349 10^{-3}	0.0511 10^{-6}	0.0771 10^{-6}	22.0068 10^{-6}	8119.8090 10^{-6}
Standard Deviation	0.57	0.030 10^{-6}	0.673 10^{-3}	0.04	0.56	0.06	0.20	0.517 10^{-3}	0.0006 10^{-6}	0.0049 10^{-6}	0.3527 10^{-6}	95.0096 10^{-6}
Maximum Relative Error (%)	0.90	4.03	4.10	0.46	4.11	0.27	0.26	4.67	4.10	24.92	6.10	4.03
Minimum Relative Error (%)	0.10	1.06	1.12	0.08	1.12	0.02	0.06	0.25	1.16	3.35	0.00	1.05

Table 4.19. Error analysis results of the diesel fuel for DOC only after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DOC only												
Biodiesel (100 Nm)												
1	101.01	1.354 10^{-6}	32.280 10^{-3}	25.60	26.87	80.00	290.00	19.995 10^{-3}	0.0300 10^{-6}	0.0683 10^{-6}	5.1376 10^{-6}	4267.6529 10^{-6}
2	101.01	1.383 10^{-6}	32.431 10^{-3}	25.50	27.00	80.00	289.00	19.995 10^{-3}	0.0302 10^{-6}	0.0674 10^{-6}	5.8494 10^{-6}	4380.5406 10^{-6}
3	100.03	1.318 10^{-6}	30.805 10^{-3}	25.60	25.65	80.00	289.00	19.995 10^{-3}	0.0287 10^{-6}	0.0639 10^{-6}	5.9434 10^{-6}	4172.5095 10^{-6}
4	101.01	1.399 10^{-6}	32.562 10^{-3}	25.50	27.12	80.00	287.00	19.995 10^{-3}	0.0304 10^{-6}	0.0676 10^{-6}	6.3830 10^{-6}	4431.2988 10^{-6}
5	100.03	1.479 10^{-6}	34.537 10^{-3}	25.70	28.76	80.00	289.00	19.995 10^{-3}	0.0322 10^{-6}	0.0701 10^{-6}	6.8269 10^{-6}	4682.7803 10^{-6}
Average	100.62	1.386 10^{-6}	32.523 10^{-3}	25.58	27.08	80.00	288.80	19.995 10^{-3}	0.0303 10^{-6}	0.0901 10^{-6}	6.0280 10^{-6}	4386.9564 10^{-6}
Standard Deviation	0.24	0.027 10^{-6}	0.595 10^{-3}	0.04	0.50	0.00	0.49	0.000 10^{-3}	0.0006 10^{-6}	0.0014 10^{-6}	0.2825 10^{-6}	86.5275 10^{-6}
Maximum Relative Error (%)	0.58	6.83	6.24	0.47	6.27	0.00	0.62	0.00	6.31	5.14	17.33	6.93
Minimum Relative Error (%)	0.39	0.25	0.12	0.08	0.14	0.00	0.07	0.00	0.19	0.15	1.65	0.15
Biodiesel (200 Nm)												
1	200.05	2.401 10^{-6}	51.630 10^{-3}	26.20	43.03	80.10	314.00	43.989 10^{-3}	0.0479 10^{-6}	0.0901 10^{-6}	16.1794 10^{-6}	7594.8396 10^{-6}
2	199.07	2.399 10^{-6}	51.434 10^{-3}	26.30	42.91	80.10	313.00	42.656 10^{-3}	0.0477 10^{-6}	0.0945 10^{-6}	16.3249 10^{-6}	7591.5043 10^{-6}
3	199.07	2.369 10^{-6}	50.793 10^{-3}	26.40	42.36	80.00	313.00	43.989 10^{-3}	0.0471 10^{-6}	0.0886 10^{-6}	15.7285 10^{-6}	7491.8737 10^{-6}
4	200.05	2.373 10^{-6}	50.968 10^{-3}	26.30	42.51	80.10	313.00	42.656 10^{-3}	0.0473 10^{-6}	0.0913 10^{-6}	16.2622 10^{-6}	7508.2136 10^{-6}
5	200.05	2.357 10^{-6}	50.621 10^{-3}	26.10	42.22	80.10	313.00	43.189 10^{-3}	0.0470 10^{-6}	0.0861 10^{-6}	15.9895 10^{-6}	7461.5779 10^{-6}
Average	199.66	2.380 10^{-6}	51.089 10^{-3}	26.26	42.61	80.08	313.20	43.296 10^{-3}	0.0474 10^{-6}	0.0901 10^{-6}	16.0969 10^{-6}	7529.6018 10^{-6}
Standard Deviation	0.24	0.009 10^{-6}	0.191 10^{-3}	0.05	0.16	0.02	0.20	0.299 10^{-3}	0.0002 10^{-6}	0.0014 10^{-6}	0.1080 10^{-6}	27.0148 10^{-6}
Maximum Relative Error (%)	0.29	0.97	1.06	0.61	1.00	0.10	0.26	1.60	1.03	4.87	2.29	0.90
Minimum Relative Error (%)	0.20	0.29	0.24	0.15	0.21	0.02	0.06	0.25	0.23	0.04	0.51	0.28

Table 4.20. Error analysis results of the biodiesel fuel for SiC only after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DPF only												
SiC only												
Biodiesel (100 Nm)												
1	98.07	1.391 10^{-6}	33.248 10^{-3}	26.80	28.36	80.10	293.00	21.328 10^{-3}	3.7806 10^{-6}	0.2699 10^{-6}	15.9462 10^{-6}	4391.2940 10^{-6}
2	96.10	1.398 10^{-6}	32.901 10^{-3}	26.80	28.07	80.20	292.00	21.328 10^{-3}	3.7863 10^{-6}	0.2925 10^{-6}	16.0518 10^{-6}	4434.4353 10^{-6}
3	96.10	1.379 10^{-6}	32.427 10^{-3}	26.90	27.67	80.00	290.00	19.995 10^{-3}	3.7306 10^{-6}	0.2792 10^{-6}	15.9843 10^{-6}	4373.9022 10^{-6}
4	101.01	1.359 10^{-6}	31.603 10^{-3}	27.00	26.98	80.00	291.00	21.328 10^{-3}	3.3978 10^{-6}	0.2500 10^{-6}	16.1926 10^{-6}	4311.6884 10^{-6}
5	101.01	1.437 10^{-6}	33.471 10^{-3}	27.00	28.57	80.00	291.00	21.328 10^{-3}	3.6618 10^{-6}	0.2571 10^{-6}	17.1122 10^{-6}	4557.4752 10^{-6}
Average	98.46	1.393 10^{-6}	32.730 10^{-3}	26.90	27.93	80.06	291.40	21.061 10^{-3}	3.6714 10^{-6}	0.2074 10^{-6}	16.2574 10^{-6}	4413.7590 10^{-6}
Standard Deviation	1.10	0.013 10^{-6}	0.332 10^{-3}	0.04	0.28	0.04	0.51	0.267 10^{-3}	0.0720 10^{-6}	0.0050 10^{-6}	0.2178 10^{-6}	40.9838 10^{-6}
Maximum Relative Error (%)	2.60	3.16	3.39	0.37	3.36	0.17	0.55	5.00	7.24	8.43	5.36	3.27
Minimum Relative Error (%)	0.40	0.16	0.51	0.00	0.50	0.05	0.14	1.25	0.25	0.06	0.41	0.47
Biodiesel (200 Nm)												
1	194.17	2.479 10^{-6}	53.066 10^{-3}	27.40	45.33	80.10	318.00	43.989 10^{-3}	3.0617 10^{-6}	0.2224 10^{-6}	42.2836 10^{-6}	7862.9732 10^{-6}
2	194.17	2.470 10^{-6}	52.865 10^{-3}	27.40	45.16	80.00	318.00	45.322 10^{-3}	3.0501 10^{-6}	0.2094 10^{-6}	42.2083 10^{-6}	7833.2277 10^{-6}
3	199.07	2.521 10^{-6}	53.761 10^{-3}	27.50	45.94	80.00	319.00	45.322 10^{-3}	3.1510 10^{-6}	0.2104 10^{-6}	43.9956 10^{-6}	7995.2104 10^{-6}
4	197.11	2.417 10^{-6}	51.491 10^{-3}	27.50	44.00	80.00	319.00	45.322 10^{-3}	2.9701 10^{-6}	0.1920 10^{-6}	41.7602 10^{-6}	7665.2530 10^{-6}
5	196.13	2.549 10^{-6}	54.362 10^{-3}	27.50	46.47	80.00	319.00	44.789 10^{-3}	3.0354 10^{-6}	0.2028 10^{-6}	44.3776 10^{-6}	8086.8267 10^{-6}
Average	196.13	2.487 10^{-6}	53.109 10^{-3}	27.46	45.38	80.02	318.60	44.949 10^{-3}	3.0537 10^{-6}	0.2074 10^{-6}	42.9251 10^{-6}	7888.6982 10^{-6}
Standard Deviation	0.93	0.023 10^{-6}	0.483 10^{-3}	0.02	0.41	0.02	0.24	0.261 10^{-3}	0.0290 10^{-6}	0.0050 10^{-6}	0.5262 10^{-6}	72.2033 10^{-6}
Maximum Relative Error (%)	1.50	2.83	3.05	0.22	3.04	0.10	0.19	2.14	3.19	7.41	3.38	2.83
Minimum Relative Error (%)	0.00	0.32	0.08	0.15	0.10	0.02	0.13	0.36	0.12	0.95	1.49	0.33

Table 4.21. Error analysis results of the diesel fuel for SiC only after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DPF only												
SiC only												
Diesel (100 Nm)												
1	97.09	1.369 10^{-6}	32.215 10^{-3}	26.50	26.95	80.00	300.00	23.994 10^{-3}	3.7366 10^{-6}	0.3831 10^{-6}	15.4752 10^{-6}	4306.1938 10^{-6}
2	97.09	1.329 10^{-6}	31.269 10^{-3}	26.40	26.16	80.00	297.00	22.661 10^{-3}	3.6440 10^{-6}	0.5194 10^{-6}	15.5562 10^{-6}	4199.4756 10^{-6}
3	98.07	1.338 10^{-6}	31.448 10^{-3}	26.40	26.31	80.00	297.00	22.661 10^{-3}	3.6354 10^{-6}	0.4773 10^{-6}	11.3289 10^{-6}	4227.9266 10^{-6}
4	98.07	1.320 10^{-6}	30.999 10^{-3}	26.30	25.94	80.10	297.00	22.661 10^{-3}	3.5269 10^{-6}	0.4993 10^{-6}	15.5836 10^{-6}	4173.5187 10^{-6}
5	99.05	1.471 10^{-6}	34.589 10^{-3}	26.30	28.95	80.00	297.00	23.994 10^{-3}	4.0014 10^{-6}	0.5541 10^{-6}	17.2330 10^{-6}	4653.6017 10^{-6}
Average	97.87	1.365 10^{-6}	32.104 10^{-3}	26.38	26.86	80.02	297.60	23.194 10^{-3}	3.7089 10^{-6}	0.5684 10^{-6}	15.0354 10^{-6}	4312.1433 10^{-6}
Standard Deviation	0.37	0.028 10^{-6}	0.653 10^{-3}	0.04	0.55	0.02	0.60	0.327 10^{-3}	0.0803 10^{-6}	0.0111 10^{-6}	0.9832 10^{-6}	88.2135 10^{-6}
Maximum Relative Error (%)	1.21	7.75	7.71	0.45	7.75	0.10	0.80	3.33	7.83	27.02	23.95	7.93
Minimum Relative Error (%)	0.20	0.25	0.34	0.08	0.32	0.03	0.20	2.22	0.74	2.43	2.84	0.14
Diesel (200 Nm)												
1	198.09	2.411 10^{-6}	51.780 10^{-3}	26.60	43.36	80.00	328.00	47.988 10^{-3}	3.6053 10^{-6}	0.6090 10^{-6}	39.3319 10^{-6}	7624.0089 10^{-6}
2	197.11	2.283 10^{-6}	49.045 10^{-3}	26.80	41.09	80.10	328.00	47.988 10^{-3}	3.5048 10^{-6}	0.5676 10^{-6}	37.4715 10^{-6}	7219.0100 10^{-6}
3	197.11	2.379 10^{-6}	51.008 10^{-3}	26.80	42.73	80.00	328.00	47.988 10^{-3}	3.6920 10^{-6}	0.5645 10^{-6}	38.6497 10^{-6}	7521.9587 10^{-6}
4	198.09	2.327 10^{-6}	49.948 10^{-3}	26.80	41.85	80.00	328.00	47.988 10^{-3}	3.4771 10^{-6}	0.5598 10^{-6}	38.0215 10^{-6}	7360.2418 10^{-6}
5	197.11	2.371 10^{-6}	50.988 10^{-3}	26.80	42.73	80.00	327.00	47.988 10^{-3}	3.6929 10^{-6}	0.5412 10^{-6}	38.4001 10^{-6}	7501.4657 10^{-6}
Average	197.50	2.354 10^{-6}	50.554 10^{-3}	26.76	42.35	80.02	327.80	47.988 10^{-3}	3.5944 10^{-6}	0.5684 10^{-6}	38.3749 10^{-6}	7445.3370 10^{-6}
Standard Deviation	0.24	0.022 10^{-6}	0.476 10^{-3}	0.04	0.40	0.02	0.20	0.000 10^{-3}	0.0453 10^{-6}	0.0111 10^{-6}	0.3109 10^{-6}	70.5018 10^{-6}
Maximum Relative Error (%)	0.30	3.02	2.98	0.60	2.99	0.10	0.24	0.00	3.26	7.13	2.49	3.04
Minimum Relative Error (%)	0.20	0.73	0.86	0.15	0.89	0.02	0.06	0.00	0.30	0.14	0.07	0.75

Table 4.22. Error analysis results of the biodiesel fuel for cordierite only after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DPF only												
Cordierite only												
Biodiesel (100 Nm)												
1	97.09	1.437 10^{-6}	33.890 10^{-3}	26.30	28.77	80.00	291.00	22.661 10^{-3}	3.8786 10^{-6}	0.2746 10^{-6}	17.0002 10^{-6}	4532.6487 10^{-6}
2	97.09	1.420 10^{-6}	33.317 10^{-3}	26.50	28.29	80.00	290.00	22.661 10^{-3}	3.7958 10^{-6}	0.2664 10^{-6}	16.9207 10^{-6}	4496.5044 10^{-6}
3	97.09	1.427 10^{-6}	33.284 10^{-3}	26.50	28.27	80.00	290.00	22.661 10^{-3}	3.7917 10^{-6}	0.2615 10^{-6}	17.0362 10^{-6}	4520.9149 10^{-6}
4	97.09	1.420 10^{-6}	33.140 10^{-3}	26.50	28.16	80.00	289.00	22.661 10^{-3}	3.7764 10^{-6}	0.2482 10^{-6}	17.1667 10^{-6}	4497.8390 10^{-6}
5	97.09	1.437 10^{-6}	33.475 10^{-3}	26.60	28.44	80.00	290.00	22.661 10^{-3}	3.7193 10^{-6}	0.2366 10^{-6}	17.5480 10^{-6}	4551.2715 10^{-6}
Average	97.09	1.428 10^{-6}	33.421 10^{-3}	26.48	28.39	80.00	290.00	22.661 10^{-3}	3.7924 10^{-6}	0.1932 10^{-6}	17.1344 10^{-6}	4519.8357 10^{-6}
Standard Deviation	0.00	0.004 10^{-6}	0.129 10^{-3}	0.05	0.11	0.00	0.32	0.000 10^{-3}	0.0255 10^{-6}	0.0048 10^{-6}	0.1108 10^{-6}	10.4445 10^{-6}
Maximum Relative Error (%)	0.00	0.61	1.38	0.68	1.34	0.00	0.34	0.00	2.22	7.58	2.43	0.69
Minimum Relative Error (%)	0.00	0.06	0.16	0.08	0.19	0.00	0.00	0.00	0.02	1.46	0.19	0.02
Biodiesel (200 Nm)												
1	196.13	2.528 10^{-6}	54.171 10^{-3}	26.90	46.07	80.00	318.00	47.988 10^{-3}	3.1732 10^{-6}	0.2094 10^{-6}	45.0204 10^{-6}	8011.9852 10^{-6}
2	196.13	2.492 10^{-6}	53.092 10^{-3}	26.90	45.17	80.00	319.00	47.988 10^{-3}	3.0608 10^{-6}	0.1954 10^{-6}	44.3802 10^{-6}	7899.1737 10^{-6}
3	195.15	2.606 10^{-6}	55.693 10^{-3}	27.00	47.39	80.10	317.00	46.655 10^{-3}	3.1594 10^{-6}	0.1922 10^{-6}	46.2948 10^{-6}	8263.0802 10^{-6}
4	192.21	2.622 10^{-6}	56.140 10^{-3}	27.10	47.78	80.10	316.00	47.988 10^{-3}	3.2886 10^{-6}	0.1886 10^{-6}	46.2468 10^{-6}	8311.5787 10^{-6}
5	194.17	2.502 10^{-6}	53.663 10^{-3}	27.10	45.68	80.10	316.00	47.721 10^{-3}	3.0449 10^{-6}	0.1803 10^{-6}	44.5305 10^{-6}	7932.2396 10^{-6}
Average	194.76	2.550 10^{-6}	54.552 10^{-3}	27.00	46.42	80.06	317.20	47.668 10^{-3}	3.1454 10^{-6}	0.1932 10^{-6}	45.2945 10^{-6}	8083.6115 10^{-6}
Standard Deviation	0.73	0.027 10^{-6}	0.587 10^{-3}	0.04	0.50	0.02	0.58	0.258 10^{-3}	0.0440 10^{-6}	0.0048 10^{-6}	0.4124 10^{-6}	85.5100 10^{-6}
Maximum Relative Error (%)	1.31	2.84	2.91	0.37	2.93	0.07	0.57	2.13	4.55	8.38	2.21	2.82
Minimum Relative Error (%)	0.20	0.86	0.70	0.00	0.75	0.05	0.06	0.11	0.45	0.50	0.61	0.89

Table 4.23. Error analysis results of the diesel fuel for cordierite only after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DPF only												
Cordierite only												
Diesel (100 Nm)												
1	99.05	1.326 10^{-6}	31.174 10^{-3}	25.70	26.08	80.10	298.00	21.328 10^{-3}	3.6253 10^{-6}	0.3488 10^{-6}	15.7673 10^{-6}	4182.4241 10^{-6}
2	98.07	1.352 10^{-6}	31.690 10^{-3}	25.50	26.52	80.00	297.00	21.328 10^{-3}	3.7040 10^{-6}	0.4399 10^{-6}	16.1980 10^{-6}	4287.0980 10^{-6}
3	99.05	1.393 10^{-6}	32.723 10^{-3}	25.40	27.39	80.00	297.00	21.328 10^{-3}	3.8582 10^{-6}	0.4834 10^{-6}	16.6342 10^{-6}	4420.6529 10^{-6}
4	98.07	1.385 10^{-6}	32.600 10^{-3}	25.50	27.29	80.00	296.00	21.328 10^{-3}	3.8126 10^{-6}	0.5177 10^{-6}	16.5298 10^{-6}	4393.7615 10^{-6}
5	99.05	1.366 10^{-6}	32.049 10^{-3}	25.50	26.83	80.00	298.00	22.661 10^{-3}	3.7776 10^{-6}	0.5326 10^{-6}	16.2993 10^{-6}	4332.9433 10^{-6}
Average	98.65	1.365 10^{-6}	32.047 10^{-3}	25.52	26.82	80.02	297.20	21.595 10^{-3}	3.7555 10^{-6}	0.5604 10^{-6}	16.2857 10^{-6}	4323.3760 10^{-6}
Standard Deviation	0.24	0.012 10^{-6}	0.287 10^{-3}	0.05	0.24	0.02	0.37	0.267 10^{-3}	0.0412 10^{-6}	0.0144 10^{-6}	0.1513 10^{-6}	42.2445 10^{-6}
Maximum Relative Error (%)	0.59	2.92	2.80	0.70	2.85	0.10	0.40	5.00	3.59	33.18	3.29	3.37
Minimum Relative Error (%)	0.40	0.12	0.01	0.08	0.03	0.02	0.07	1.25	0.61	5.42	0.09	0.23
Diesel (200 Nm)												
1	199.07	2.405 10^{-6}	51.958 10^{-3}	25.80	43.51	80.00	326.00	45.322 10^{-3}	3.7254 10^{-6}	0.6034 10^{-6}	39.8166 10^{-6}	7627.9046 10^{-6}
2	199.07	2.340 10^{-6}	50.460 10^{-3}	25.70	42.26	80.00	327.00	45.322 10^{-3}	3.6186 10^{-6}	0.5628 10^{-6}	38.4036 10^{-6}	7423.9264 10^{-6}
3	195.15	2.313 10^{-6}	49.878 10^{-3}	26.80	41.77	80.00	327.00	45.322 10^{-3}	3.5637 10^{-6}	0.5543 10^{-6}	37.6633 10^{-6}	7311.3973 10^{-6}
4	195.15	2.352 10^{-6}	50.516 10^{-3}	25.90	42.31	80.00	327.00	45.322 10^{-3}	3.6675 10^{-6}	0.5677 10^{-6}	38.8754 10^{-6}	7457.2264 10^{-6}
5	196.13	2.346 10^{-6}	50.449 10^{-3}	25.80	42.26	80.10	327.00	45.322 10^{-3}	3.6640 10^{-6}	0.5137 10^{-6}	38.6782 10^{-6}	7442.8355 10^{-6}
Average	196.92	2.351 10^{-6}	50.652 10^{-3}	26.00	42.42	80.02	326.80	45.322 10^{-3}	3.6478 10^{-6}	0.5604 10^{-6}	38.6874 10^{-6}	7452.6580 10^{-6}
Standard Deviation	0.90	0.015 10^{-6}	0.347 10^{-3}	0.20	0.29	0.02	0.20	0.000 10^{-3}	0.0270 10^{-6}	0.0144 10^{-6}	0.3493 10^{-6}	50.7980 10^{-6}
Maximum Relative Error (%)	1.10	2.29	2.58	3.08	2.57	0.10	0.24	0.00	2.31	8.32	2.92	2.35
Minimum Relative Error (%)	0.40	0.02	0.27	0.38	0.25	0.02	0.06	0.00	0.44	0.43	0.02	0.06

Table 4.24. Error analysis results of the biodiesel fuel for DOC+SiC after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DOC+DPF												
DOC+SiC												
Biodiesel (100 Nm)												
1	101.01	1.381 10^{-6}	32.158 10^{-3}	26.20	26.93	80.00	296.00	26.660 10^{-3}	0.0299 10^{-6}	0.0681 10^{-6}	4.8297 10^{-6}	4364.6367 10^{-6}
2	99.05	1.396 10^{-6}	32.568 10^{-3}	26.30	27.28	80.00	294.00	26.660 10^{-3}	0.0304 10^{-6}	0.0587 10^{-6}	4.9756 10^{-6}	4429.7315 10^{-6}
3	97.09	1.455 10^{-6}	34.097 10^{-3}	26.40	28.56	80.00	292.00	26.660 10^{-3}	0.0318 10^{-6}	0.0567 10^{-6}	5.2129 10^{-6}	4617.3990 10^{-6}
4	96.10	1.533 10^{-6}	35.956 10^{-3}	26.40	30.12	80.00	290.00	26.660 10^{-3}	0.0336 10^{-6}	0.0582 10^{-6}	5.6740 10^{-6}	4864.4053 10^{-6}
5	98.07	1.427 10^{-6}	33.284 10^{-3}	26.30	27.89	80.00	291.00	26.660 10^{-3}	0.0311 10^{-6}	0.0508 10^{-6}	5.5154 10^{-6}	4528.9895 10^{-6}
Average	98.26	1.439 10^{-6}	33.613 10^{-3}	26.32	28.15	80.00	292.60	26.660 10^{-3}	0.0314 10^{-6}	0.0706 10^{-6}	5.2415 10^{-6}	4561.0324 10^{-6}
Standard Deviation	0.84	0.027 10^{-6}	0.672 10^{-3}	0.04	0.56	0.00	1.08	0.000 10^{-3}	0.0006 10^{-6}	0.0013 10^{-6}	0.1586 10^{-6}	87.1924 10^{-6}
Maximum Relative Error (%)	2.72	6.86	7.29	0.46	7.29	0.00	1.15	0.00	7.40	14.08	8.95	6.95
Minimum Relative Error (%)	0.19	0.86	1.02	0.08	0.99	0.00	0.20	0.00	0.90	0.31	0.59	0.73
Biodiesel (200 Nm)												
1	196.13	2.512 10^{-6}	53.817 10^{-3}	26.50	45.09	80.10	319.00	55.986 10^{-3}	0.0500 10^{-6}	0.0693 10^{-6}	16.8249 10^{-6}	7968.9544 10^{-6}
2	198.09	2.536 10^{-6}	54.231 10^{-3}	26.40	45.44	80.00	319.00	57.319 10^{-3}	0.0504 10^{-6}	0.0724 10^{-6}	17.3887 10^{-6}	8047.9508 10^{-6}
3	196.13	2.525 10^{-6}	53.887 10^{-3}	26.40	45.15	80.00	319.00	57.319 10^{-3}	0.0501 10^{-6}	0.0744 10^{-6}	17.7041 10^{-6}	8011.6833 10^{-6}
4	199.07	2.531 10^{-6}	54.111 10^{-3}	26.40	45.34	80.00	319.00	55.986 10^{-3}	0.0503 10^{-6}	0.0697 10^{-6}	17.9362 10^{-6}	8029.5877 10^{-6}
5	196.13	2.526 10^{-6}	54.011 10^{-3}	26.60	45.25	80.00	318.00	56.786 10^{-3}	0.0502 10^{-6}	0.0671 10^{-6}	18.0620 10^{-6}	8009.2883 10^{-6}
Average	197.11	2.526 10^{-6}	54.011 10^{-3}	26.46	45.25	80.02	318.80	56.679 10^{-3}	0.0502 10^{-6}	0.0706 10^{-6}	17.5832 10^{-6}	8013.4929 10^{-6}
Standard Deviation	0.62	0.004 10^{-6}	0.075 10^{-3}	0.04	0.06	0.02	0.20	0.299 10^{-3}	0.0001 10^{-6}	0.0013 10^{-6}	0.2215 10^{-6}	13.1359 10^{-6}
Maximum Relative Error (%)	1.00	0.55	0.41	0.53	0.41	0.10	0.25	1.22	0.43	5.40	4.31	0.56
Minimum Relative Error (%)	0.50	0.00	0.00	0.15	0.01	0.02	0.06	0.19	0.05	1.21	0.69	0.02

Table 4.25. Error analysis results of the diesel fuel for DOC+SiC after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DOC+DPF												
DOC+SiC												
Diesel (100 Nm)												
1	100.03	1.337 10^{-6}	31.071 10^{-3}	25.50	26.24	80.00	300.00	26.660 10^{-3}	0.0289 10^{-6}	0.0543 10^{-6}	5.0734 10^{-6}	4226.4365 10^{-6}
2	101.01	1.377 10^{-6}	31.904 10^{-3}	25.50	26.94	80.00	301.00	27.993 10^{-3}	0.0298 10^{-6}	0.0531 10^{-6}	5.3328 10^{-6}	4371.9588 10^{-6}
3	101.01	1.376 10^{-6}	31.933 10^{-3}	25.60	26.97	80.00	301.00	27.993 10^{-3}	0.0298 10^{-6}	0.0546 10^{-6}	5.3872 10^{-6}	4365.5113 10^{-6}
4	100.03	1.363 10^{-6}	31.607 10^{-3}	25.60	26.70	80.00	302.00	27.993 10^{-3}	0.0295 10^{-6}	0.0540 10^{-6}	5.3868 10^{-6}	4325.6332 10^{-6}
5	101.01	1.395 10^{-6}	32.311 10^{-3}	25.50	27.29	80.00	301.00	27.993 10^{-3}	0.0302 10^{-6}	0.0553 10^{-6}	5.6581 10^{-6}	4427.7631 10^{-6}
Average	100.62	1.370 10^{-6}	31.765 10^{-3}	25.54	26.83	80.00	301.00	27.726 10^{-3}	0.0296 10^{-6}	0.0812 10^{-6}	5.3677 10^{-6}	4343.4606 10^{-6}
Standard Deviation	0.24	0.010 10^{-6}	0.207 10^{-3}	0.02	0.17	0.00	0.32	0.267 10^{-3}	0.0002 10^{-6}	0.0002 10^{-6}	0.0930 10^{-6}	33.4797 10^{-6}
Maximum Relative Error (%)	0.59	2.42	2.23	0.24	2.24	0.00	0.33	4.00	2.57	2.17	5.80	2.77
Minimum Relative Error (%)	0.39	0.46	0.45	0.16	0.45	0.00	0.00	1.00	0.44	0.15	0.38	0.42
Diesel (200 Nm)												
1	197.11	2.390 10^{-6}	50.825 10^{-3}	25.80	42.94	80.00	332.00	55.986 10^{-3}	0.0472 10^{-6}	0.0818 10^{-6}	14.5731 10^{-6}	7580.9905 10^{-6}
2	199.07	2.360 10^{-6}	50.314 10^{-3}	25.70	42.51	80.00	332.00	57.319 10^{-3}	0.0468 10^{-6}	0.0810 10^{-6}	14.2739 10^{-6}	7486.3159 10^{-6}
3	198.09	2.370 10^{-6}	50.442 10^{-3}	25.80	42.62	80.10	338.00	57.319 10^{-3}	0.0469 10^{-6}	0.0812 10^{-6}	14.5439 10^{-6}	7516.8880 10^{-6}
4	197.11	2.376 10^{-6}	50.653 10^{-3}	25.70	42.79	80.00	332.00	57.319 10^{-3}	0.0471 10^{-6}	0.0816 10^{-6}	14.6111 10^{-6}	7536.8660 10^{-6}
5	199.07	2.351 10^{-6}	49.990 10^{-3}	25.80	42.24	80.10	332.00	57.052 10^{-3}	0.0465 10^{-6}	0.0805 10^{-6}	14.5042 10^{-6}	7456.8383 10^{-6}
Average	198.09	2.369 10^{-6}	50.445 10^{-3}	25.76	42.62	80.04	333.20	56.999 10^{-3}	0.0469 10^{-6}	0.0812 10^{-6}	14.5012 10^{-6}	7515.5798 10^{-6}
Standard Deviation	0.44	0.007 10^{-6}	0.144 10^{-3}	0.02	0.12	0.02	1.20	0.258 10^{-3}	0.0001 10^{-6}	0.0002 10^{-6}	0.0595 10^{-6}	21.2607 10^{-6}
Maximum Relative Error (%)	0.50	0.89	0.90	0.23	0.90	0.07	1.44	1.78	0.92	0.92	1.57	0.87
Minimum Relative Error (%)	0.00	0.03	0.01	0.16	0.01	0.05	0.36	0.09	0.02	0.02	0.02	0.02

Table 4.26. Error analysis results of the biodiesel fuel for DOC+Cordierite after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DOC+DPF												
DOC+Cordierite												
Biodiesel (100 Nm)												
1	101.99	1.427 10^{-6}	33.194 10^{-3}	27.50	28.36	80.00	296.00	26.660 10^{-3}	0.0310 10^{-6}	0.0506 10^{-6}	4.9544 10^{-6}	4523.1197 10^{-6}
2	101.01	1.401 10^{-6}	32.525 10^{-3}	27.50	27.78	80.00	295.00	26.660 10^{-3}	0.0305 10^{-6}	0.0482 10^{-6}	5.1433 10^{-6}	4459.5084 10^{-6}
3	99.05	1.423 10^{-6}	33.023 10^{-3}	27.50	28.20	80.00	294.00	26.660 10^{-3}	0.0309 10^{-6}	0.0490 10^{-6}	5.3835 10^{-6}	4527.7793 10^{-6}
4	100.03	1.434 10^{-6}	33.286 10^{-3}	27.40	28.43	80.00	293.00	26.660 10^{-3}	0.0312 10^{-6}	0.0478 10^{-6}	5.5319 10^{-6}	4565.0171 10^{-6}
5	101.01	1.491 10^{-6}	34.563 10^{-3}	27.30	29.51	80.10	292.00	26.660 10^{-3}	0.0324 10^{-6}	0.0481 10^{-6}	5.9743 10^{-6}	4745.2800 10^{-6}
Average	100.62	1.435 10^{-6}	33.318 10^{-3}	27.44	28.46	80.02	294.00	26.660 10^{-3}	0.0312 10^{-6}	0.0601 10^{-6}	5.3975 10^{-6}	4564.1409 10^{-6}
Standard Deviation	0.50	0.015 10^{-6}	0.338 10^{-3}	0.04	0.29	0.02	0.71	0.000 10^{-3}	0.0003 10^{-6}	0.0006 10^{-6}	0.1749 10^{-6}	48.3555 10^{-6}
Maximum Relative Error (%)	1.54	3.88	3.75	0.51	3.72	0.10	0.68	0.00	3.86	3.61	11.64	4.00
Minimum Relative Error (%)	0.38	0.08	0.10	0.15	0.10	0.03	0.00	0.00	0.00	0.47	0.28	0.02
Biodiesel (200 Nm)												
1	198.09	2.533 10^{-6}	53.964 10^{-3}	27.50	46.08	80.00	322.00	54.653 10^{-3}	0.0503 10^{-6}	0.0622 10^{-6}	16.9163 10^{-6}	8058.2783 10^{-6}
2	196.13	2.520 10^{-6}	54.281 10^{-3}	27.60	46.35	80.00	319.00	54.653 10^{-3}	0.0506 10^{-6}	0.0601 10^{-6}	16.8436 10^{-6}	8012.6198 10^{-6}
3	197.11	2.522 10^{-6}	53.782 10^{-3}	27.60	45.93	80.00	320.00	54.653 10^{-3}	0.0501 10^{-6}	0.0596 10^{-6}	17.8055 10^{-6}	8023.0962 10^{-6}
4	195.15	2.523 10^{-6}	53.534 10^{-3}	27.50	45.72	80.00	321.00	54.653 10^{-3}	0.0499 10^{-6}	0.0593 10^{-6}	17.7252 10^{-6}	8025.9481 10^{-6}
5	195.15	2.526 10^{-6}	53.666 10^{-3}	27.70	45.84	80.10	321.00	54.653 10^{-3}	0.0500 10^{-6}	0.0594 10^{-6}	17.8605 10^{-6}	8033.4831 10^{-6}
Average	196.33	2.525 10^{-6}	53.845 10^{-3}	27.58	45.98	80.02	320.60	54.653 10^{-3}	0.0502 10^{-6}	0.0601 10^{-6}	17.4302 10^{-6}	8030.6851 10^{-6}
Standard Deviation	0.57	0.002 10^{-6}	0.130 10^{-3}	0.04	0.11	0.02	0.51	0.000 10^{-3}	0.0001 10^{-6}	0.0006 10^{-6}	0.2260 10^{-6}	7.6668 10^{-6}
Maximum Relative Error (%)	0.90	0.34	0.81	0.44	0.79	0.10	0.50	0.00	0.84	3.53	3.37	0.34
Minimum Relative Error (%)	0.10	0.06	0.12	0.07	0.11	0.02	0.12	0.00	0.12	0.00	1.69	0.03

Table 4.27. Error analysis results of the diesel fuel for DOC+Cordierite after treatment system

Test No.	T (Nm)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{air}$ (kg/s)	$T_{air,in}$ (°C)	$\dot{V}_{air}$ (L/s)	T_{cw} (°C)	T_{exh} (°C)	P_{exh} (bar)	$\dot{m}_{CO}$ (kg/s)	$\dot{m}_{HC}$ (kg/s)	$\dot{m}_{NO_x}$ (kg/s)	$\dot{m}_{CO_2}$ (kg/s)
DOC+DPF												
DOC+Cordierite												
Diesel (100 Nm)												
1	101.99	1.368 10^{-6}	31.913 10^{-3}	25.50	26.71	80.00	302.00	26.660 10^{-3}	0.0297 10^{-6}	0.0471 10^{-6}	4.1719 10^{-6}	4326.4924 10^{-6}
2	101.99	1.371 10^{-6}	31.925 10^{-3}	25.30	26.73	80.00	301.00	25.327 10^{-3}	0.0299 10^{-6}	0.0488 10^{-6}	4.4512 10^{-6}	4360.2218 10^{-6}
3	101.01	1.467 10^{-6}	34.167 10^{-3}	25.20	28.60	80.00	301.00	25.327 10^{-3}	0.0320 10^{-6}	0.0475 10^{-6}	4.5971 10^{-6}	4667.6269 10^{-6}
4	100.03	1.362 10^{-6}	31.676 10^{-3}	25.30	26.54	80.00	300.00	25.327 10^{-3}	0.0297 10^{-6}	0.0455 10^{-6}	4.4562 10^{-6}	4333.8118 10^{-6}
5	101.01	1.370 10^{-6}	31.969 10^{-3}	25.30	26.76	80.00	298.00	25.327 10^{-3}	0.0299 10^{-6}	0.0459 10^{-6}	4.6075 10^{-6}	4356.9616 10^{-6}
Average	101.20	1.388 10^{-6}	32.330 10^{-3}	25.32	27.07	80.00	300.40	25.594 10^{-3}	0.0302 10^{-6}	0.0653 10^{-6}	4.4568 10^{-6}	4409.0229 10^{-6}
Standard Deviation	0.37	0.020 10^{-6}	0.462 10^{-3}	0.05	0.39	0.00	0.68	0.267 10^{-3}	0.0004 10^{-6}	0.0008 10^{-6}	0.0786 10^{-6}	64.9754 10^{-6}
Maximum Relative Error (%)	1.15	5.83	5.76	0.71	5.75	0.00	0.79	4.00	5.90	3.92	6.83	5.98
Minimum Relative Error (%)	0.19	1.21	1.13	0.08	1.14	0.00	0.13	1.00	1.05	0.22	0.01	1.13
Diesel (200 Nm)												
1	199.07	2.473 10^{-6}	53.082 10^{-3}	25.80	44.44	80.10	330.00	53.320 10^{-3}	0.0494 10^{-6}	0.0660 10^{-6}	13.2688 10^{-6}	7849.4397 10^{-6}
2	197.11	2.355 10^{-6}	50.454 10^{-3}	25.90	42.24	80.10	330.00	53.320 10^{-3}	0.0469 10^{-6}	0.0627 10^{-6}	11.7233 10^{-6}	7472.3601 10^{-6}
3	198.09	2.451 10^{-6}	52.552 10^{-3}	25.90	44.00	80.10	330.00	53.320 10^{-3}	0.0489 10^{-6}	0.0677 10^{-6}	13.8006 10^{-6}	7775.8067 10^{-6}
4	197.11	2.340 10^{-6}	50.170 10^{-3}	25.80	42.00	80.00	330.00	53.320 10^{-3}	0.0467 10^{-6}	0.0647 10^{-6}	13.1795 10^{-6}	7425.8450 10^{-6}
5	197.11	2.358 10^{-6}	50.568 10^{-3}	25.90	42.34	80.10	329.00	53.320 10^{-3}	0.0470 10^{-6}	0.0652 10^{-6}	13.4519 10^{-6}	7482.6997 10^{-6}
Average	197.70	2.396 10^{-6}	51.365 10^{-3}	25.86	43.00	80.08	329.80	53.320 10^{-3}	0.0478 10^{-6}	0.0653 10^{-6}	13.0848 10^{-6}	7601.2302 10^{-6}
Standard Deviation	0.39	0.028 10^{-6}	0.602 10^{-3}	0.02	0.50	0.02	0.20	0.000 10^{-3}	0.0006 10^{-6}	0.0008 10^{-6}	0.3566 10^{-6}	87.6076 10^{-6}
Maximum Relative Error (%)	0.69	3.25	3.34	0.23	3.34	0.10	0.24	0.00	3.37	3.92	10.41	3.27
Minimum Relative Error (%)	0.20	1.55	1.55	0.15	1.55	0.02	0.06	0.00	1.56	0.12	0.72	1.56

5. CONCLUSIONS

In this study, the biodiesel and diesel fuels are used to operate the diesel engine at various engine loads (100 Nm, 200 Nm and 294 Nm) without after treatment system and with DOC & DPF after treatment systems. The fuels are tested 5 times for with and without after treatment systems, and the average values are taken into account. The experimental, energy, exergy, economic and environmental analyses are applied to the system. The following main conclusions can be obtained from this study:

- Most of the exhaust emissions (except NO_x) are inversely proportional to the engine load. If the engine load increases, the exhaust emissions decrease (except NO_x).
- The CO_2 and NO_x emission rates of the biodiesel fuel are generally more than the diesel fuel, while the CO and HC emissions of the biodiesel fuel rates are less than the diesel fuel. In this study, when the biodiesel fuel is used, it causes less CO and HC and more CO_2 and NO_x than the diesel fuel.
- The LHV of the biodiesel fuel, which is obtained from cooking oil, is less than the LHV of the diesel fuel.
- Maximum specific fuel consumption is found for the biodiesel fuel, while minimum rate is determined for the diesel fuel. The specific fuel consumption of the system is inversely proportional to the LHV of the fuel.
- The particle concentration of the biodiesel fuel is less than the diesel fuel. Moreover, the maximum total particle concentrations are calculated at 100 Nm torque for both of the fuel types and the particle concentrations of the fuels are inversely proportional to the engine load. If the engine load increases, the particle concentration decreases.
- The soot concentration is inversely proportional to the engine load. The soot concentration of the biodiesel fuel is less than the diesel fuel. So, the biodiesel fuel is better option for less soot and better environment. In addition, if the biodiesel fuel is used at higher engine load, soot concentration can be decreased.
- The biodiesel fuel has better energy efficiency than the diesel fuel at every engine loads. Also, the energy efficiency is directly proportional to the engine load.

- The biodiesel fuel has higher exergy efficiency than the diesel fuel at every engine load. In addition, the biodiesel fuel causes less exergy destruction than the diesel fuel.
- When the engine load increases, the entropy generation of the system increases. The entropy generation is directly proportional to the engine load.
- The environmental and enviroeconomic parameters are directly proportional to the engine load. If the engine is used at high loads, it causes more CO_2 emission. The minimum CO_2 emission releasing in a day is calculated at 100 Nm torque.
- The sustainability index is directly proportional to the engine loads. The minimum sustainability index is found at 100 Nm for both fuels. In addition, biodiesel fuel is better option for sustainable future for diesel engines.
- If the engine load decreases, thermoeconomic parameter (energy loss rate per capital cost) also decreases. Therefore, the thermoeconomic parameter is directly proportional to the engine loads.
- The exergoeconomic parameter (exergy loss and destruction per capital cost) is maximum at 294 Nm torque for without after treatment, while it is maximum at 200 Nm torque for after treatment system. It is also minimum at 100 Nm torque for all systems (with or without after treatment). The biodiesel fuel is better option for exergoeconomic aspect.
- When the DOC is used with cordierite diesel particulate filter, the exhaust emission particle reduction rate is found as 98.57%. If the DOC is used with a SiC diesel particle filter, 99.97% of the emission of the exhaust emission particulate can be avoided. Despite the fact that there is little difference, the SiC diesel particulate filter prevents more exhaust emission particle than cordierite.
- At 100 Nm engine load, the biodiesel fuel has 40.09% less total nanoparticle concentration than the diesel fuel for without after treatment system.
- At 200 Nm engine load, the biodiesel fuel has 54.07% less total nanoparticle concentration than the diesel fuel for without after treatment system.
- At 294 Nm engine load, the biodiesel fuel has 58.44% less total nanoparticle concentration than the diesel fuel for without after treatment system.
- At 100 Nm engine load, the biodiesel fuel has 34.54% less total nanoparticle concentration than the diesel fuel for DOC only.

- At 200 Nm engine load, the biodiesel fuel has 52.76% less total nanoparticle concentration than the diesel fuel for DOC only.
- At 100 Nm engine load, the biodiesel fuel has 2.34% less total nanoparticle concentration than the diesel fuel for SiC only.
- At 200 Nm engine load, the biodiesel fuel has 41.55% less total nanoparticle concentration than the diesel fuel for SiC only.
- At 100 Nm engine load, the biodiesel fuel has 51.89% less total nanoparticle concentration than the diesel fuel for cordierite only.
- At 200 Nm engine load, the biodiesel fuel has 2.21% less total nanoparticle concentration than the diesel fuel for cordierite only.
- At 100 Nm engine load, the biodiesel fuel has 54.05% less total nanoparticle concentration than the diesel fuel for DOC+SiC.
- At 200 Nm engine load, the biodiesel fuel has 53.45% less total nanoparticle concentration than the diesel fuel for DOC+SiC.
- At 100 Nm engine load, the biodiesel fuel has 72.71% less total nanoparticle concentration than the diesel fuel for DOC+Cordierite.
- At 200 Nm engine load, the biodiesel fuel has 35.69% less total nanoparticle concentration than the diesel fuel for DOC+Cordierite.
- At 100 Nm engine load, the biodiesel fuel has 18.16% less entropy generation than the diesel fuel for without after treatment system.
- At 200 Nm engine load, the biodiesel fuel has 17.12% less entropy generation than the diesel fuel for without after treatment system.
- At 294 Nm engine load, the biodiesel fuel has 19.43% less entropy generation than the diesel fuel for without after treatment system.
- At 100 Nm engine load, the biodiesel fuel has 21.78% less entropy generation than the diesel fuel for DOC only.
- At 200 Nm engine load, the biodiesel fuel has 16.01% less entropy generation than the diesel fuel for DOC only.
- At 100 Nm engine load, the biodiesel fuel has 22.49% less entropy generation than the diesel fuel for SiC only.
- At 200 Nm engine load, the biodiesel fuel has 18.84% less entropy generation than the diesel fuel for SiC only.

- At 100 Nm engine load, the biodiesel fuel has 18.51% less entropy generation than the diesel fuel for cordierite only.
- At 200 Nm engine load, the biodiesel fuel has 15.09% less entropy generation than the diesel fuel for cordierite only.
- At 100 Nm engine load, the biodiesel fuel has 17.90% less entropy generation than the diesel fuel for DOC+SiC.
- At 200 Nm engine load, the biodiesel fuel has 17.57% less entropy generation than the diesel fuel for DOC+SiC.
- At 100 Nm engine load, the biodiesel fuel has 20.44% less entropy generation than the diesel fuel for DOC+Cordierite.
- At 200 Nm engine load, the biodiesel fuel has 18.43% less entropy generation than the diesel fuel for DOC+Cordierite.

The biodiesel fuel is more effective than the diesel fuel in terms of efficiency, environmental and economic aspects. The biodiesel fuel has also less total nanoparticle concentration and entropy generation than the diesel fuel for every engine load and after treatment option (with and without after treatment).

Thanks to the utilization of DOC and DPF, more than 90% reduction of nanoparticles can cause to increase the usability and sustainability of diesel engines. Thus, diesel engines can become more environmentally friendly. In this context, it is expected that this study will contribute to the spread of the use of diesel engines environmentally friently for many years.

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