Engine Performance and Emission Characteristics using Biodiesel - B100

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Project Scope

Literature Review & Standards Revision (Completed)	→ Biodiesel Quality Test (Completed)	→ Engine Performance Studies (Ongoing)	→ Sea Trials (Ongoing)

Methodology and Key Outcomes

Literature Review & Standards Revision (Completed)

Methodology:

- Desktop Literature Studies
- Case Study Analysis
- Review Papers

(A) Effect of different types of additives
(B) Role of B100 biodiesel as pilot fuel

Standards Reviews:

- EN 14214
- ISO 8217
- ASTM D6751
- WA2 - 2022

Key Outcomes:

- Literature reviews show that antioxidants enhance resistance to oxidation
- Reviews of the standards help to determine the 11 parameters for biodiesel quality test

Biodiesel Quality Test (Completed)

Methodology:

- Laboratory Experiments
- 11 parameters tested:
  - ❑ FAME content
  - ❑ Copper strip corrosion
  - ❑ Density at 15ºC
  - ❑ Oxidation stability
  - ❑ Water content
  - ❑ Calorific value
  - ❑ Acid value
  - ❑ Lubricity
  - ❑ Viscosity at 40ºC
  - ❑ Microbial contamination
  - ❑ Cetane number

Key Outcomes:

- Effects of additives + biodiesel blends over long term storage
- Results of the biodiesel quality test serve as a baseline for types of blend (additives + biodiesel) for sea trial

Engine Performance Studies (Ongoing)

Methodology:

- Survey with engine makers
- Testbed Study
- CFD Analysis

Key Outcomes:

- Statistical analysis of the application of biodiesel + additives on engine performance, which serve as a baseline for sea trial
- CFD analysis determines the engine performance over a longer period

Sea Trials (Ongoing)

Methodology:

- Port / Vessel Recce
- Port-Data Collection (200 hrs)
- Data Analysis

Bunker Tanker

Tugboat

Key Outcomes:

1. Operational Efficiency
2. Emission Performance
3. Data Analysis

Background

- FAME biodiesel's overall lifecycle carbon footprint is lower compared to traditional diesel
- Used Cooking Oil Methyl Ester (UCOME) is one type of FAME that tends to be less stable than other FAME biodiesel
- Antioxidants are chemical substances that inhibit the oxidation of fatty acid oils or esters by neutralizing free radicals at the initiation stage of oxidation

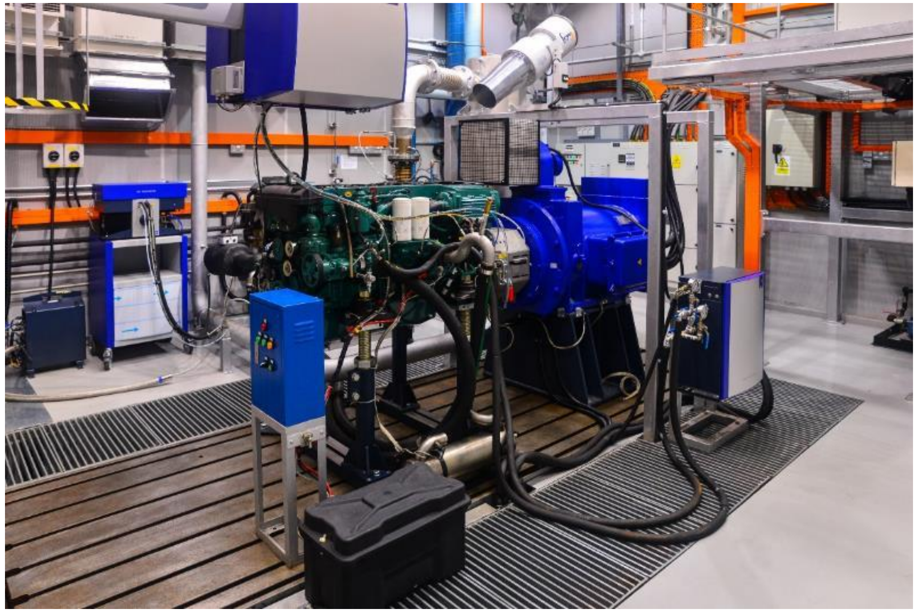
Testbed study objectives

- Aims to investigate the influence of various antioxidant additives on the **engine performance** and **emission characteristics** of a marine engine fueled with pure biodiesel and,
- Attempts to assess the **performance compatibility** of antioxidant addition into B100 usage in conventional marine diesel engines.

Table 1. List of Engine Key Parameters

Engine Type	Volvo Penta D6-370
Displacement (L)	5.5
Number of Cylinders	6
Bore x Stroke (mm)	103 x 110
Connecting Rod Length (mm)	164
Compression Ratio	17.5
Maximum Power (kW)	272
Speed Range (rpm)	600 – 3500
Fuel Injector	Common Rail

Key Parameters Measured/Derived		
Performance	**Combustion**	**Emission**
Engine Speed	In Cylinder Pressure	Carbon Dioxide(CO_2)
Power	Heat Release Rate	Carbon Monoxide(CO)
Torque	Ignition Delay	Total Hydrocarbons(THC)
Brake Thermal Efficiency	Combustion Duration	Nitrogen Oxides(NO_x)
Brake Specific Fuel Consumption	Maximum Pressure Rise Rate	Smoke Opacity



Fuel Properties

Table 2. List of Diesel and B100 Properties

Fuel Type	Diesel[a]	B100 UCOME[b]
Average Chemical Formula	$C_{10.8}H_{18.7}$	$C_{18.7}H_{35.0}O_2$[c]
Density (kg/m^3)	830	874
Cetane Number	52	61
Lower Heating Value (MJ/kg)	42.45	36.88
Stoichiometric Air-Fuel Ratio	14.3	14

[a] [22]. [b] Actual values measured via separated fuel properties tests. [c] [23]

- The biodiesel LHV is **13.12%** lower than that of diesel.
- From chemical composition tests, the mass percentage of carbon, hydrogen, and oxygen of biodiesel are **76.79%**, **12.60%** and **10.60%,** respectively.
- The B100 UCOME is dosed with three different fuel additives (A, B, and AD) to study their impact on engine performance and emissions.

Used Cooking Oil Methyl Ester (UCOME) B100 Biodiesel

Additive A

Additive B

Additive AD

Methodology

1. Fixed fuel mass experiment
2. Fixed torque/power experiment
3. Aged fuel experiment

Fixed fuel mass test → Fixed torque/power test → Aged fuel test

Examine the effect of direct change from diesel to B100 without additional adjustment to fuel injection

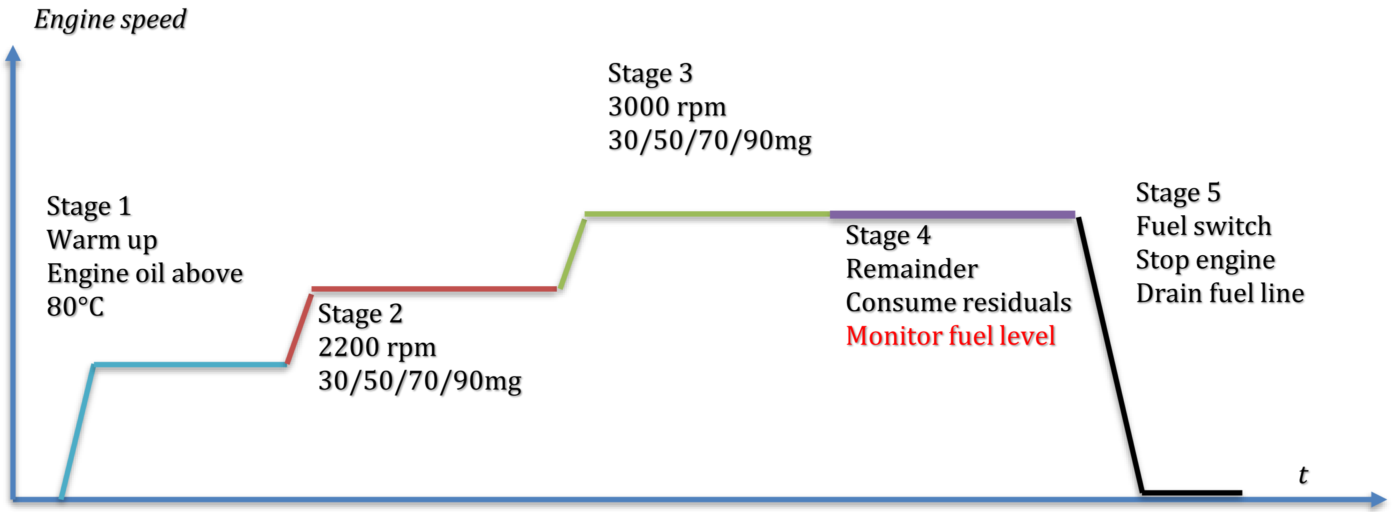
Fuel throttle is adjusted to keep the power output constant, before and after fuel change

Fuel samples are stored over 4.5 months before used in engine, to assess the effect of biodiesel degradation over long period of time

Test 1: Fixed Fuel Mass

Test 1: Fixed Fuel Mass - Steady State Performance + Emission Test				
Fuel Sample	**Engine Speed (rpm)**	**Fuel Mass (mg)**	**Fuel Injection**	**Fuel Temperature(°C)**
Diesel Baseline	2200/3000	30/50/70/90	15°CA BTDC, single pulse	30
B100 UCOME				
B100 UCOME + A				
B100 UCOME + B				
B100 UCOME + AD				

1. The experiments are conducted on a **fixed fuel mass basis**
2. Two engine speed level are used (2200rpm – intermediate speed, 3000rpm – rated speed)
3. Fuel mass refers to the setting value of the amount of fuel injected per cylinder per engine cycle



Test Profile (repeated for five samples)

Test 1: Fixed Fuel Mass

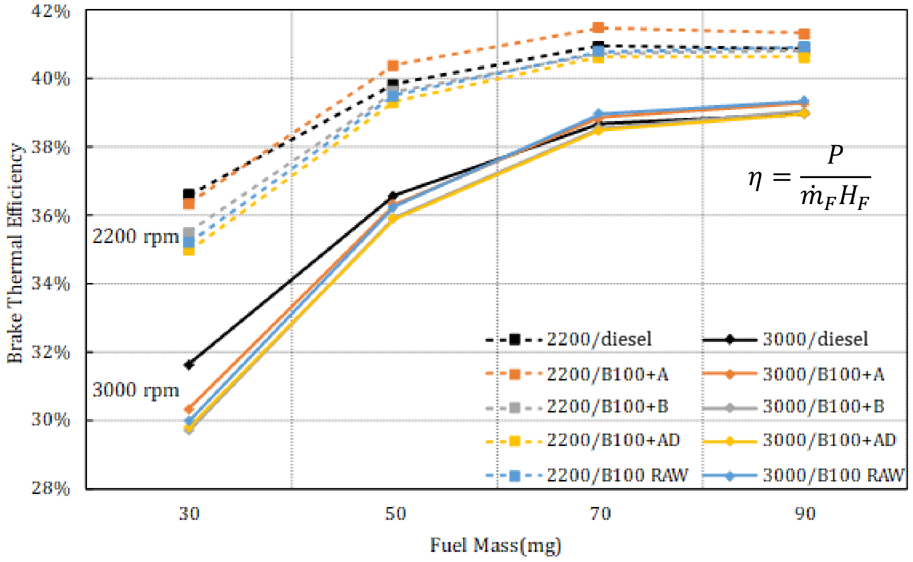


Figure 1. Engine Brake Thermal Efficiencies at 2200 and 3000 rpm

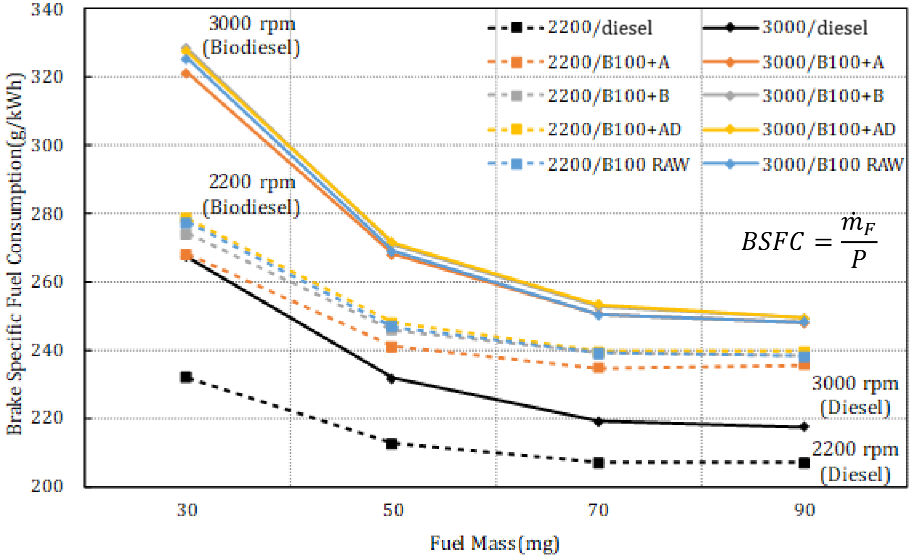


Figure 2. Engine Brake Specific Fuel Consumptions at 2200 and 3000 rpm

- Biodiesel groups produce on average **12.33%** and **12.17%** less power output at 2200 and 3000 rpm, compared to conventional diesel fuel.

- The difference in power output is closely mirroring the difference in their lower heating values, which is **13.12%**. Despite this lower power output, biodiesel groups maintain comparable levels of brake thermal efficiency to conventional diesel.

- Due to the reduced energy content of biodiesel, the brake specific fuel consumption is higher for biodiesel groups.

Table 3. Average power output of different fuel groups, at 2200rpm and 3000rpm

	diesel	B100+A	B100+B	B100+AD	B100 RAW
Power, 2200rpm(kW)	118.80	106.13	103.85	103.51	103.12
Δ%	-	-10.66%	-12.59%	-12.87%	-13.20%
Power, 3000rpm(kW)	150.38	132.98	131.62	131.86	131.86
Δ%	-	-11.57%	-12.47%	-12.32%	-12.31%

Test 1: Fixed Fuel Mass

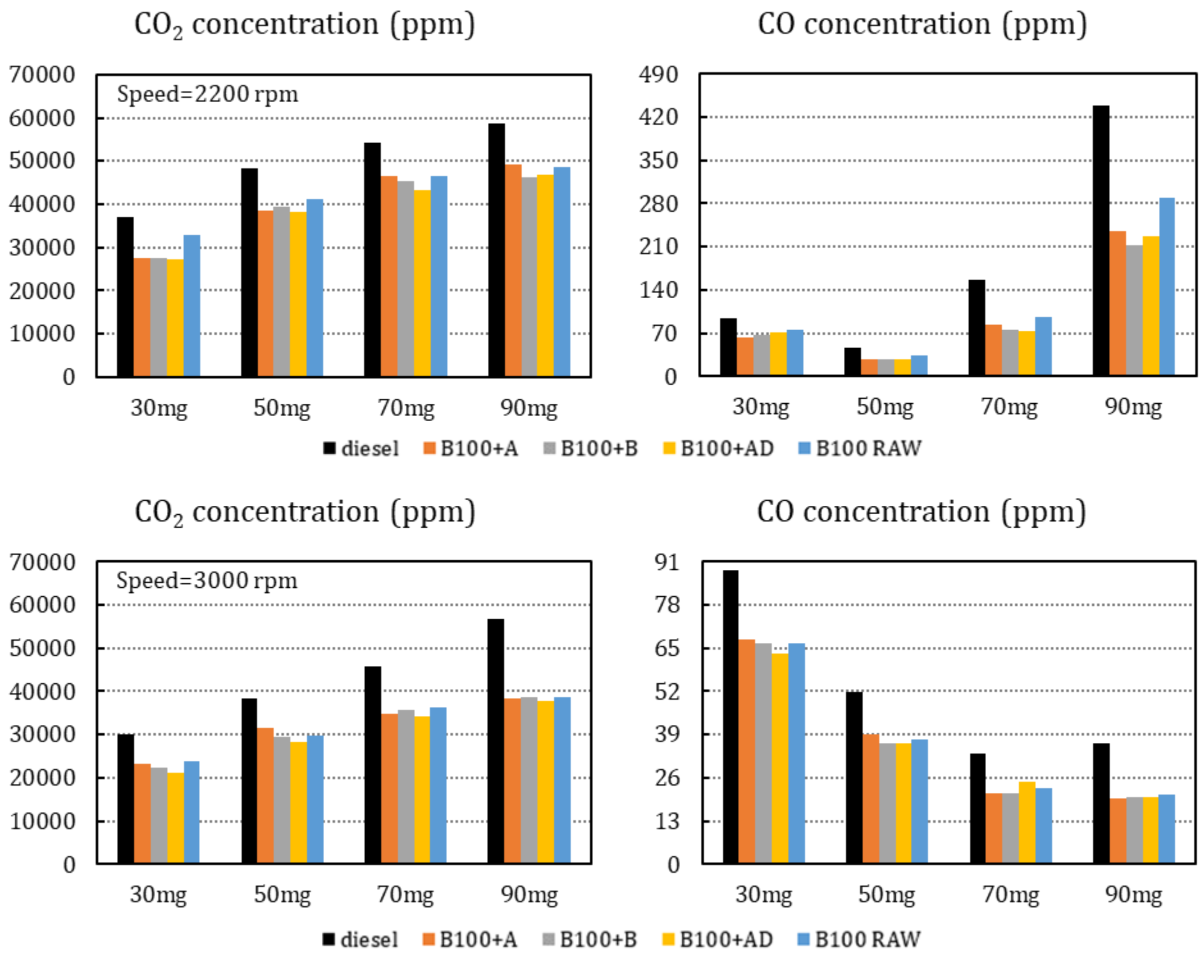


Figure 3. Emissions of CO2 and CO for different fuel groups at 2200 and 3000 rpm

- CO_2: On average, B100 results in a reduction of **18.7%** and **26.2%** in carbon dioxide emissions at engine speeds of 2200 rpm and 3000 rpm, respectively.
- This decrease is primarily due to the lower carbon content per unit mass in the biodiesel molecules.

- CO: On average, B100 achieves a **43.0%** and **30.3%** reduction in carbon monoxide emissions at engine speeds of 2200 rpm and 3000 rpm, respectively.

Test 1: Fixed Fuel Mass

- THC: On average, B100 achieves a **64.9%** and **60.4%** reduction in unburned total hydrocarbons emissions at 2200 rpm, at engine speeds of 2200 rpm and 3000 rpm, respectively.
- The improvements are attributed mainly to the additional oxygen content in the biodiesel molecules, which facilitates more complete combustion.

- Smoke/PM: Biodiesel groups demonstrate **superior performance** in terms of smoke opacity, indicating a marked improvement in particulate matter emissions.
- This advantage is mainly due to the absence of aromatic compounds in biodiesel, which are prevalent in conventional diesel and are precursors to particulate matter formation.

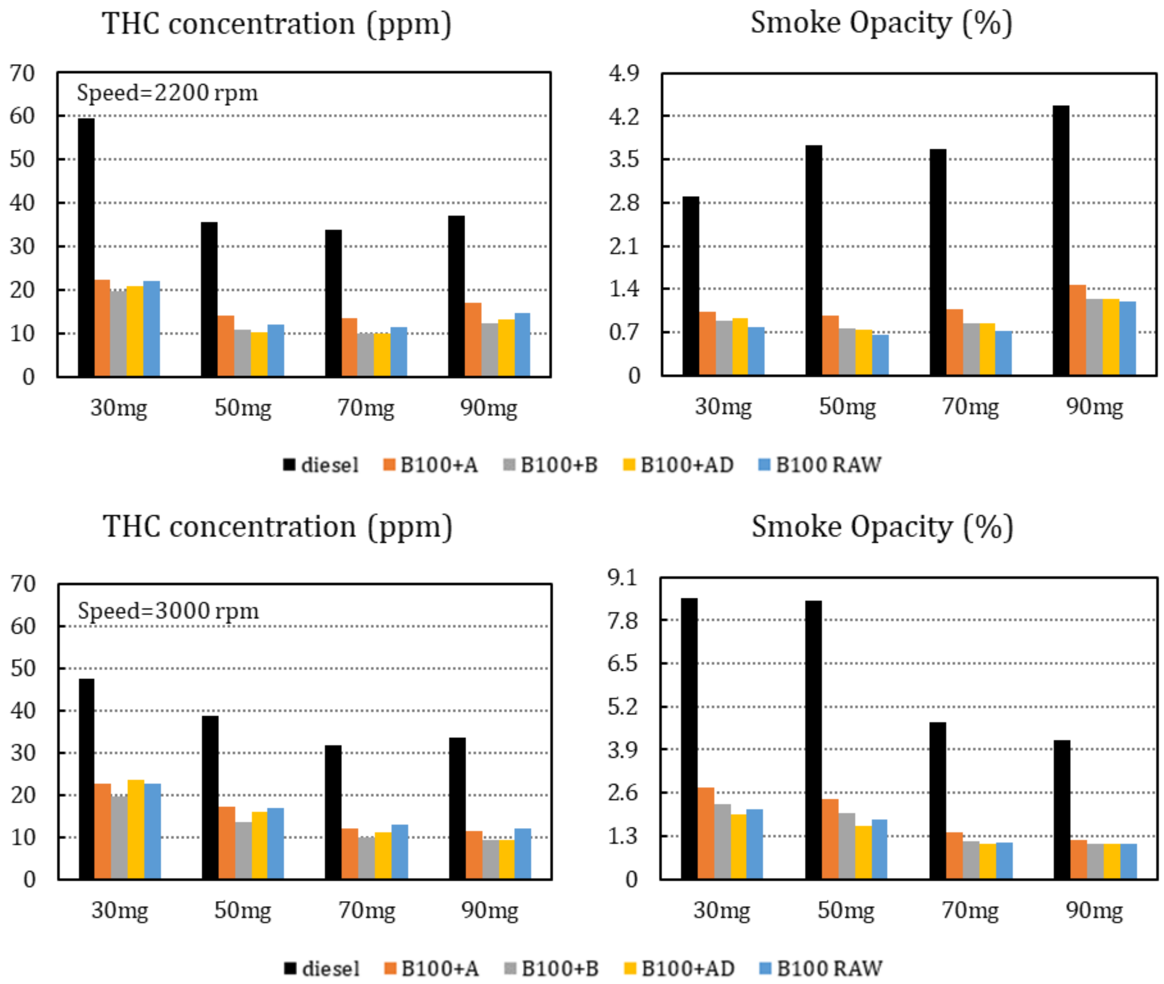


Figure 4. Emissions of THC and Smoke Opacity for different fuel groups at 2200 and 3000 rpm

Test 1: Fixed Fuel Mass

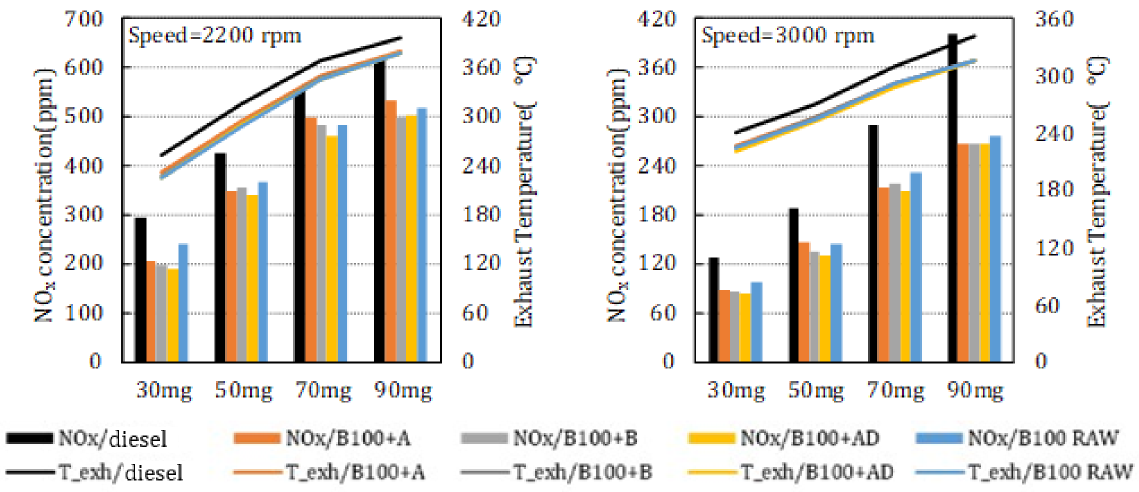


Figure 5. Emission of NO_x, and Exhaust Temperature for different fuel groups at 2200/3000 rpm

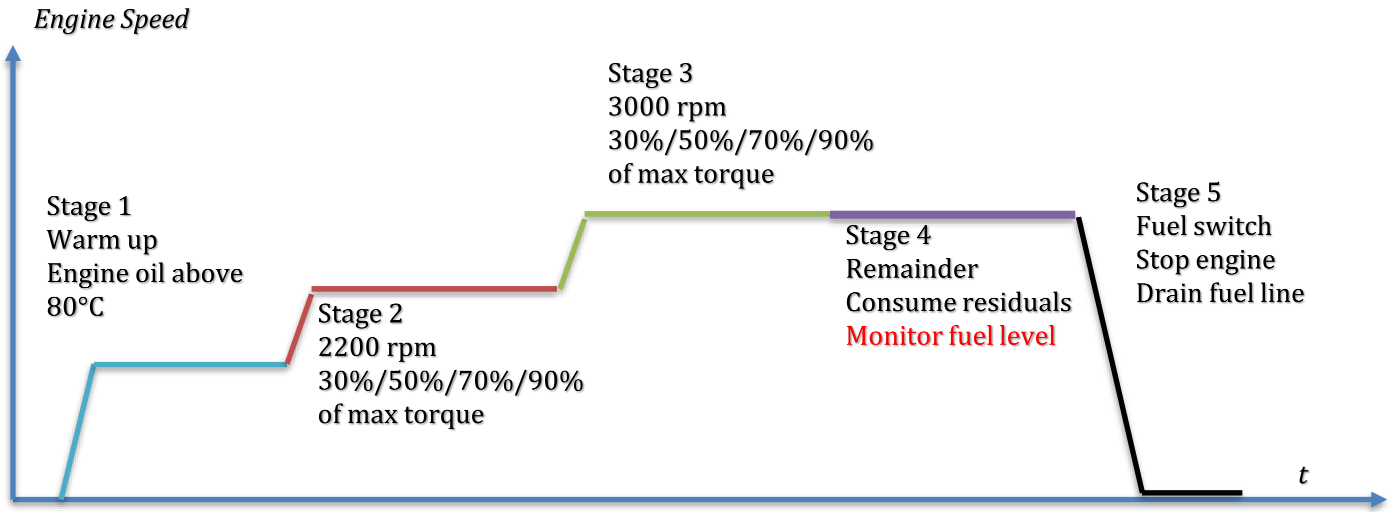
- NO_x: On average, B100 reduces nitrogen oxides emissions by **17.8%** and **28.7%** at 2200 rpm and 3000 rpm, respectively. This reduction can be attributed to the lowered combustion temperatures (15~23°C) resulting from the fuel's lower energy content.

- No noticeable differences in emissions were observed across the different additive groups, suggesting that the antioxidants used in the study do not adversely impact the fuel's emission characteristics.

- This indifference indicates that the tested antioxidants maintain the fuel stability benefits of biodiesel without compromising emission performance.

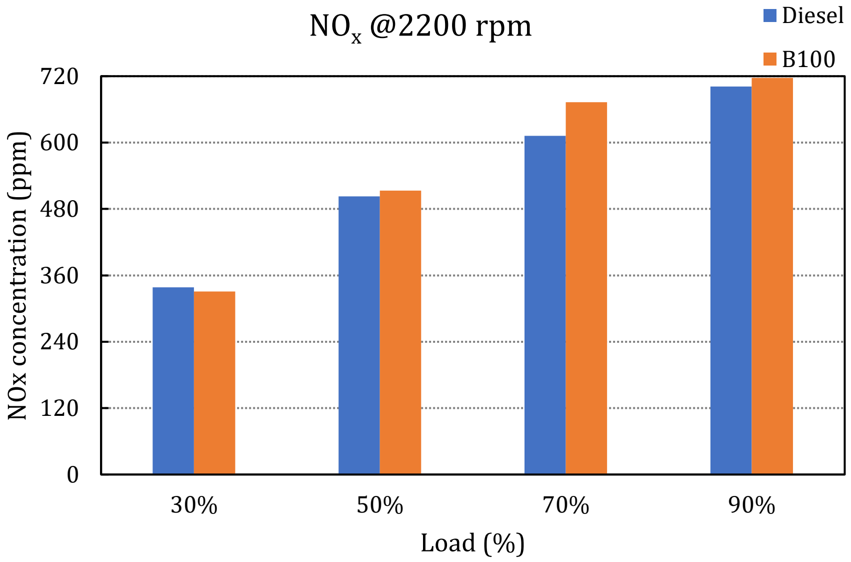
Test 2: Fixed Torque - Steady State Performance + Emission Test				
Fuel Sample	**Engine Speed (rpm)**	**Engine Torque (max%)**	**Fuel Injection**	**Fuel Temperature(°C)**
Diesel Baseline	2200/3000	30/50/70/90	15°CA BTDC, single pulse	30
B100 UCOME				

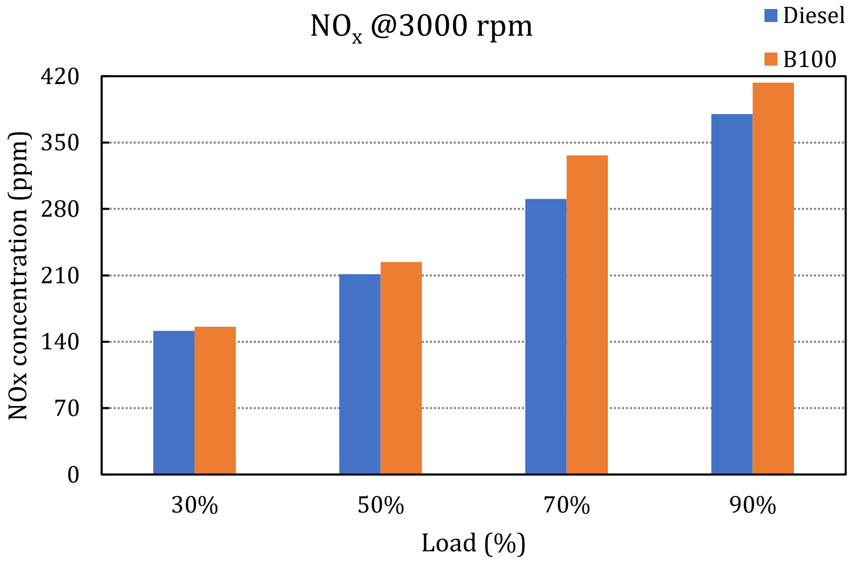
1. The experiments are conducted on a **fixed torque basis**
2. Two Speed level are used (2200rpm – intermediate speed, 3000rpm – rated speed)
3. Torque refers to the demanded value of the torque measured at shaft in steady state



Test Profile (repeated for two samples)

Test 2: Fixed Torque

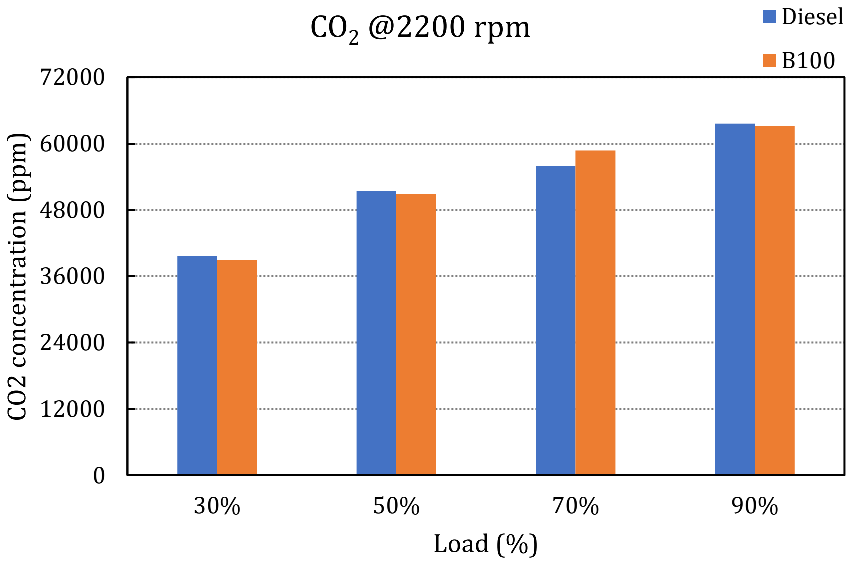


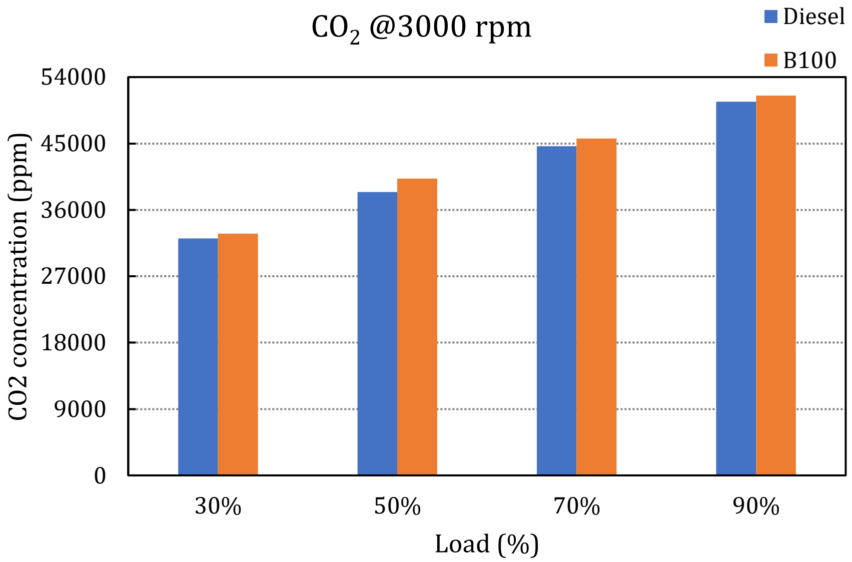


NO_x concentration (ppm)				
Engine Speed	**2200 rpm – max 850 Nm**			
Torque	**255Nm(30%)**	**425Nm(50%)**	**595Nm(70%)**	**765Nm(90%)**
Diesel	338.2	502.7	612.3	701.3
B100 UCOME	330.7	513.2	673.2	717.0
Increase	-2.23%	2.08%	9.95%	2.25%
Engine Speed	**3000 rpm – max 800 Nm**			
Torque	**240Nm(30%)**	**400Nm(50%)**	**560Nm(70%)**	**720Nm(90%)**
Diesel	151.3	211.1	290.5	380.0
B100 UCOME	155.9	224.0	336.5	413.1
Increase	3.02%	6.10%	15.85%	8.71%

- NO_x: On average, B100 increases nitrogen oxides emissions by **3.01%** and **8.42%** at 2200 rpm and 3000 rpm, respectively.
- This increase can be attributed to the additional oxygen content in the biodiesel molecule (**oxygen mass% = 10.6**) and the additional fuel consumption in keeping the **fixed torque basis**, compensating for the lower heating value of the biodiesel.
- In all test points the exhaust temperature differences between diesel and B100 are within 5°C

Test 2: Fixed Torque





CO_2 concentration (ppm)				
Engine Speed	**2200 rpm – max 850 Nm**			
Torque	**255Nm(30%)**	**425Nm(50%)**	**595Nm(70%)**	**765Nm(90%)**
Diesel	39629.9	51409.2	55999.1	63634.0
B100 UCOME	38899.6	50865.6	58770.5	63175.8
Increase	-1.84%	-1.06%	4.95%	-0.72%
Engine Speed	**3000 rpm – max 800 Nm**			
Torque	**240Nm(30%)**	**400Nm(50%)**	**560Nm(70%)**	**720Nm(90%)**
Diesel	32135.3	38436.5	44617.9	50671.6
B100 UCOME	32771.9	40239.7	45689.1	51494.3
Increase	1.98%	4.69%	2.40%	1.62%

- CO_2: On average, B100 increases carbon dioxide emissions by **0.33%** and **2.67%** at 2200 rpm and 3000 rpm, respectively. This increase is very marginal and is close to the experiment error margin.

- When adjusted for a fixed load, the additional B100 consumed to compensate for its lower LHV resulted in CO2 emissions that were comparable to, or slightly higher than, those from diesel.

Aged Fuel Experiments

- Four different biodiesel/additive combination(Raw/A/B/AD)
- Three different fuel storage periods (1.5/3/4.5months), the fuel is stored in open air shelter
- Total of 12 B100 aged sample + Month0 B100 + diesel baseline
- Each sample is tested under total of 12 operating conditions

- The aged fuel experiment has been successfully completed with all fuel samples tested recently, result is in the process of analysis and finalizing
- Preliminary data reveal that unadditized aged B100 biodiesel does not show significant deterioration in combustion or engine performance; however, during engine tests, it is associated with an increased risk of engine operational issues

Summary

Power output

- At same fuel mass, B100 biodiesel produces on average 12.33% and 12.17% less power output at 2200 and 3000 rpm
- The decrease in power output is closely mirroring the difference in lower heating values(13.12%)

Efficiency

- B100 maintains comparable levels of brake thermal efficiency to conventional diesel
- By changing to B100, there is no deterioration of combustion quality or energy conversion effectiveness
- The BSFC is higher for biodiesel groups due to the reduced energy content

CO_2 emission

- At same fuel mass, B100 reduces CO2 emission by 18.7% and 26.2%, at 2200 and 3000 rpm
- When adjusted to fixed load, B100 produced CO2 emissions that were comparable to, or slightly higher than those from diesel

NO_x emission

- At same fuel mass, B100 reduces NO_x emissions by 17.8% and 28.7%, at 2200 rpm and 3000 rpm
- When adjusted to fixed load, B100 increases NO_x emissions by 3.01% and 8.42% at 2200 rpm and 3000 rpm, respectively.

CO, THC and PM emission

- B100 reduces the CO, THC and PM emission in both fixed fuel mass and fixed load cases

Fuel additives

- Tested additives maintain the fuel stability benefits without compromising emission and performance

Thank You

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