

Characterization and effect of the use of safflower methyl ester and diesel blends in the compression ignition engine

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Abstract. Energy is vital to the profitable growth of every nation and to stimulate new research. Only natural resources can meet the growing energy demand in recent years, biodiesel has become very interested in the energy as well as environmental advantages that it can be combined with mineral diesel fuel in any quantity. The research focuses on the study of the replacement of diesel with a safflower methyl ester. The engine tests shall be performed using the safflower methyl ester as fuel in the DI diesel engine. The combustion, emission and performance characteristics were studied using alternative fuels and mixtures. Safflower Methyl Ester 80% (SAME80) and SAME100 have high heat release rates. Nitrogen oxides were higher by about 50%, carbon monoxide decreased by 10%, unburnt hydrocarbon was slightly higher and the thermal efficiency was higher for the SAME than for diesel fuel.

1 Introduction

The use of powerful diesel engines needs help in the future, as the fuel consumed is lower and potent greenhouse gases such as carbon dioxide are substantially reduced (Antolin *et al.*, 2002). The growing use of diesel, huge trade flows and environmental issues have led to developing nations like India finding an environmentally friendly alternative to diesel fuel. The country's dependence on oil-rich countries is growing due to a highly accountable energy shortage (Demirbas, 2007). It raises the country's import bill. The rise in the bill is a major concern for the lack of global trade tools and the energy supply shortages are highly responsible. Petroleum products are commonly used by transport, agriculture and industries. In the modernised agricultural sector, it plays a crucial role (Dorado *et al.*, 2003). The eradication of Internal Combustion (IC) engines cannot be achieved. To use current engines in an effective way, alternative fuel is the solution and it must be obtainable (Kinoshita *et al.*, 2004). There have been some considerations concerning the selection of suitable alternatives to petroleum-based fuels. Several steps to encourage the conservation of petroleum resources have been taken (Murugan *et al.*, 2008). These include improved refining energy production and increased transport fuel efficiency.

Furthermore, the exhaust of the engine accumulates in the air pollutants. To minimise the impact on the environment of exhaust gas emissions and the depletion of fossil fuel reserves, alternative fuels are needed. Alternatives such as fuel injector, transportation of fuel, storage and transmission should be compatible with the current engines (Schlick *et al.*, 1988).

Biofuels are typically more efficient than fossil-fuel production, but their use can lead to reducing transportation pollution (Lesnik *et al.*, 2020). In developing countries, energy demand is projected to increase by 90% and about a third of this energy will come from renewable energies, including biofuels. The only alternative to fossil fuels available in the world is biofuel from extracted biomass (Vignesh *et al.*, 2021). Safflower methyl ester oils, on the other hand, have been much favoured worldwide as edible raw material for biodiesel processing. The Compression Ignition (CI), as alternative fuel without motor modification due to high viscosity and density, is not fed with clean biodiesel up to 100% (Soares and Rocha, 2018). However, it has been shown that pure biodiesel can be used without significant energy changes in diesel engines (Ozsezen and Canakci, 2011). Oil is a material that is largely suitable for the generation of biomass fuel, particularly in oil-importing countries all over the world, such as Turkey, as an alternative source of renewable energy.

In other words, the biodiesel fuel produced from safflower oil, which is not consumed by people in this

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country like food, can be beneficial to decline the dependency on fossil fuel. Experimented soya biodiesel in the heavy-duty engine and noticed a 25% decrease in CO emission, a 77% decrease in particulate matter and a 10% rise in NO_x emission (Sharp *et al.*, 2005). Research on the advanced CI engine fuelled with soybean biodiesel (B20) and concluded that decreased emission was the outcome of CO and particulate emission. The researchers finally stated that by varying the engine attributes, namely, exhaust gas recirculation levels and injection valve timing, the performance of the engine can be enhanced (Sirman *et al.*, 2000). Safflower Methyl Ester (SAME) has been considered a replacement fuel in a diesel engine under different operating conditions, but few attempts are being made to consider it to be a fuel in a CI engine (Karabas, 2014). It has been stated that safflower oil can be converted into SAME and used as a conventional diesel fuel based on the literature review (Yesilyurt *et al.*, 2020). The work aims to study the combustion, emission and performance characteristics of the SAME and are compared with diesel.

2 Fuel preparation

A sample was prepared and the oil was bought for the experiment, hence the safflower is not accessible on a mass market. The viscosity of SAME in a diesel engine must be minimised. This is possible with transesterification, combining or pyrolysis from SAME with diesel (Yesilyurt *et al.*, 2020). For the SAME mixing preparation, more time and work is required in different methods. Although the properties of high SAME are comparable to diesel, there may also be long-term problems with engine durability. Glycerin in the SAME system can cause problems with the engine fuel injection system in its non-modified form (Tutak *et al.*, 2016). The structure will be adjusted and compliant with the engine fuel injection system by decreasing the viscosity of safflower oil using the transesterification process. This process is used to transform bio-oils with fats and large ramified triglyceride molecules into smaller molecules with straight chains close to diesel fuel molecules. A test to validate the consistency of biodiesel prepared in compliance with ASTM D 6751-07b is carried out before the characterization of SAME (Dwivedi and Sharma, 2014).

3 Experimental work

Figure 1 demonstrates the schematic view of the experimental setup. Table 1 displays the engine specifications. Tests are performed on SAME and SAME blends in stationary diesel engines. The load is applied with the power dynamometer on the generator. The torque is precisely measured using a loading cell-type pressure gauge to achieve output power.

4 Results and discussion

The findings are analysed and compared with diesel in the test on a stationary CI engine with the SAME and SAME

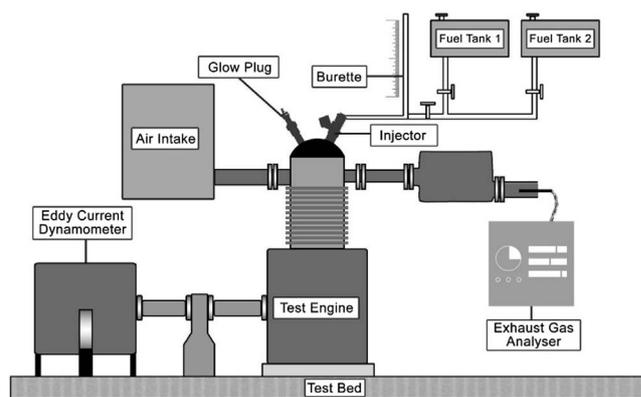


Fig. 1. Schematic view of the experimental setup.

Table 1. Engine specifications.

Engine	<i>Kirloskar</i>
Type	TAF 1
Injection-cooling	Direct injection, air-cooled
Bore × Stroke	87.5 × 110 mm
Compression ratio	17.5:1
CC	0.661 L
Indicated power	4.4 kW
Speed	1500 rpm
Injection angle	23 CAD bTDC

blend. The properties of SAME, SAME blend and diesel are shown in Table 2.

4.1 Combustion analysis

4.1.1 Combustion chamber pressure

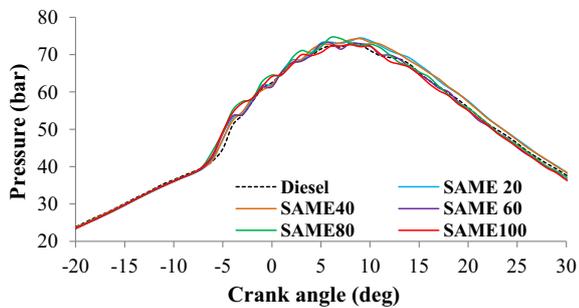
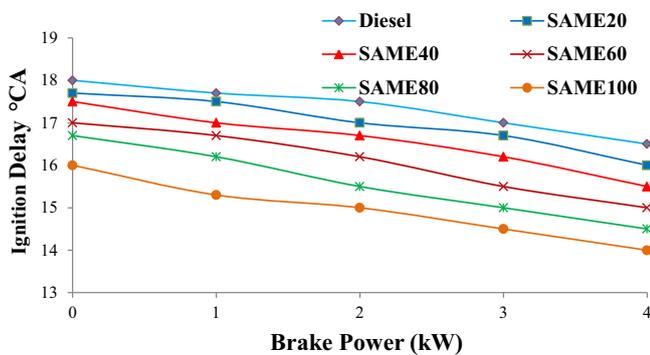
Figure 2 shows the combustion chamber pressure for the SAME, SAME blend and diesel in each crank angle at rated load. During the initial stage of combustion, the mixture of SAME and SAME will have a higher pressure compared to diesel (start of combustion at 4 CAD bTDC). The higher pressure of the SAME cylinder and its mixture during this time is due to its short ignition delay. This leads to an earlier start of combustion and also helps to increase the gaseous pressure by pushing the piston to the TDC. In the case of the SAME blends and SAME, the pressure of the cylinder is closer to TDC compared to diesel. Their lower heat release rate is mainly due to their lower heat emissions. SAME and its mixture show a slightly higher cylinder pressure (Hoekman *et al.*, 2012). The density of diesel is less than the same. During the expansion stroke, the higher-end molecules in these fatty acids burn and create a slightly higher cylinder pressure.

4.1.2 Ignition delay

In Figure 3, the variations in Brake Power (BP) with ignition delay at various loads can be seen. Fuel ignition is a

Table 2. Properties for SAME, SAME blend and diesel.

Fuel property	Testing method	Diesel	SAME	SAME blend	Standard value as per ASTM D 6751-07b
Viscosity at 40 °C (mm ² /s)	Redwood viscometer	3.3	4.1	3.62	1.9–6.0
Flashpoint (°C)	ASTM D 92	70	169	80	130 min
Calorific value (kJ/kg)	ASTM D 240-02	43 000	39 436	42 455	~38912.7
Distillation temperature T90 (°C)	ASTM D86	335	345	337	360 max
Specific gravity	–	0.850	0.889	0.845	0.88
Acid number (mg KOH/gm)	–	–	0.48	–	0.50 max
Calculated cetane index	ASTM D 4737	48.9	53.3	52.14	47 min

**Fig. 2.** Variation of combustion chamber pressure.**Fig. 3.** Difference in ignition delay.

major factor that has an inverse effect on the amount of cetane. NO_x formation takes place during the initiation of combustion and at the peak cylinder pressure. The NO_x rate is influenced by an early burning mixer compressed at high temperatures. It is expressed as the time between the start of the injection and the combustion. As soon as combustion begins, the pressure increases dramatically (Capecchi *et al.*, 2017). This raises the temperature of the braking system and reduces the delay time. The chemical reaction and polymerization of the SAME and SAME blends combine at high temperatures to ensure that the higher fatty acids of the SAME and SAME blends become lighter compounds.

4.1.3 Flue gas temperature

The variations in BP with flue gas temperatures for various loads are shown in Figure 4. For both fuels, the temperature of the flue gas increases with BP due to a higher amount of heat applied. The SAME and SAME blend temperatures are 17% higher and 9% higher than the diesel. The temperature of the SAME exhaust gas is 7° higher than the SAME blends. As a result of 10% more biodiesel than diesel, fuel injection is started earlier by the pressure inside the fuel injector. As opposed to diesel, the viscosity of the SAME and SAME blend is 24% and 10% respectively, which raises the injection pressure. Because of this advantage, the needle-shaped plunger opens faster, combustion is advanced, and the temperature of the cylinder is increased compared to diesel (Carlos *et al.*, 2014).

4.1.4 Peak pressure

Different researchers observe different patterns in varying peak pressures in methyl esters and their mixtures on diesel engines from the literature review. The peak pressures in a diesel engine are influenced by the early stage of combustion. Because of the long ignition delay in the pre-combustion stage more heat is released, the peak pressure increases. The highest pressure decrease is observed, with the increasing percentage of methyl ester. Figure 5 indicates variations in maximum pressures at varying loads for diesel, SAME and SAME blends.

More fuel is consumed at higher loads, resulting in greater peak pressures at higher loads to release more energy. Each load has a lower maximum pressure compared to diesel in the SAME and its blend. This is because their ignition delay at different loads is shorter than diesel. The flue gas produces more heat due to the high latent heat, which reduces maximum pressure and temperature (Kowalewicz and Wojtyniak, 2005).

4.1.5 Rate of heat release

Figure 6 shows the SAME and SAME blends compared to diesel which describe the rate of heat release at different angles of the crank. In the thermal release curve, the thermal energy availability potential is shown. Because the heat produced by SAME and SAME blends is low compared to diesel. In comparison with diesel, the difference in the heat

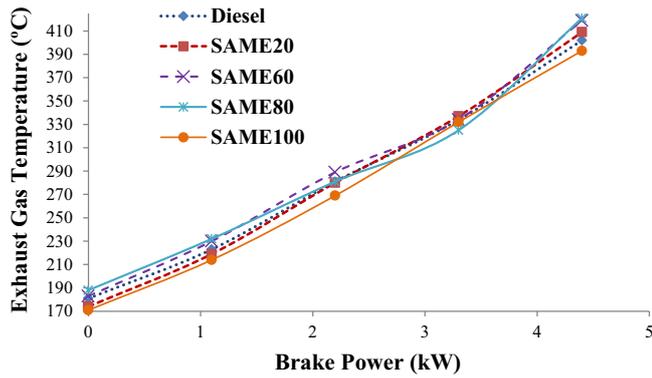


Fig. 4. Difference in flue gas temperature.

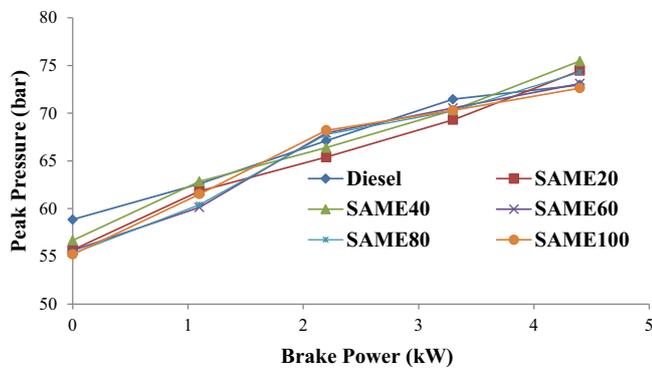


Fig. 5. Variable of peak pressure.

release rate is more significant than in the combustion chamber for the SAME80, SAME100. Since the temperature is inadequate in the combustion chamber during the early combustion stage. The heat release rate for SAME80 and SAME100 is high compared to diesel, as a result of rapid burns following TDC (Broatch *et al.*, 2014).

The overall heat release rate of the SAME and SAME blends is 42% and 24%, respectively compared to diesel, and its angle is increased by 2° due to its shorter period. It is noted that the heat produced for the SAME and SAME blends is higher than diesel in the proximity of TDC. The average fatty acid density of safflower oil was 65% higher than that present in diesel hydrocarbons.

4.1.6 Combustion duration

The amount of energy that is emitted by burning fuel is defined by the angle of release of the heat. The angle of thermal release is the angle of the crank from the start of combustion to the required produced heat (Kaulani *et al.*, 2019). Figure 7 shows the mean crank angle of time that 10%, 50% and 90% of the heat energy from the start is emitted by diesel, SAME and SAME blends at BP.

For larger BP, the volume of fuel is higher. The crank interval increases with BP to release 90% of the heat energy. For SAME and SAME blends, the combustion starts more early than diesel, so that it takes less crank

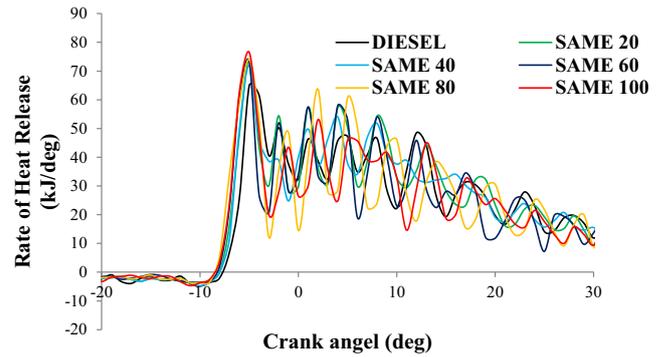


Fig. 6. Rate of heat release.

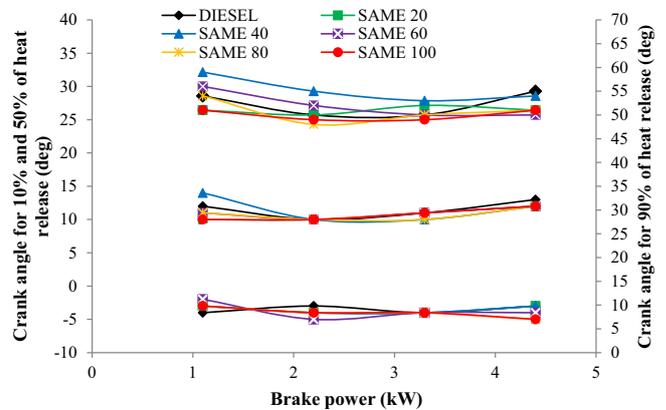


Fig. 7. Crank angle variations for 10%, 50% and 90% of heat release.

angle to produce 90% heat. For the SAME and SAME blend, the necessary crank angle is 3.8 and 3% earlier than diesel. The disparity in the crank angle of 90% for the SAME and SAME blends is shown to be less than that of diesel at different loads. Figure 8 displays the variation of combustion duration with BP.

4.2. Emission analysis

4.2.1 NO_x emission

The NO_x emissions vectors with brake power are revealed in Figure 9. NO_x emissions are constantly rising with BP. It is noted, a significant amount of fuel and continuous air supply is pumped to have the same brake power. Owing to the increase in the richness of the mixture, NO_x increases with BP. Also, the SAME and SAME blend's NO_x emission are slightly higher than the diesel emissions by about 17% and 8% respectively. The rise in BP also increases the strength of the mixture and raises the oxygen required in the SAME and SAME blends. The combustion temperature raises the emission of NO_x. SAME and SAME blends provide extra oxygen since this fuel is oxygen-based, which increases the use of free oxygen to work on nitrogen in the form of NO_x at higher combustion temperatures.

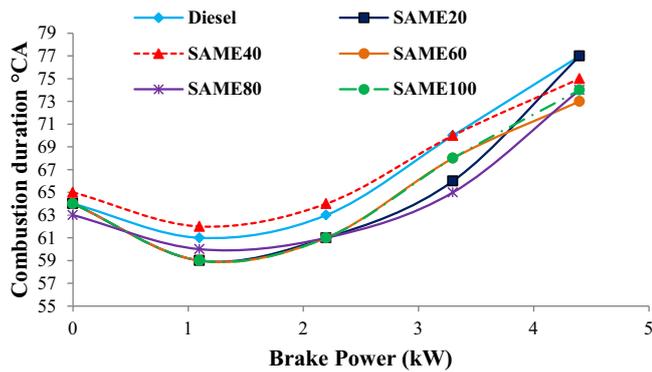


Fig. 8. Variation of combustion duration.

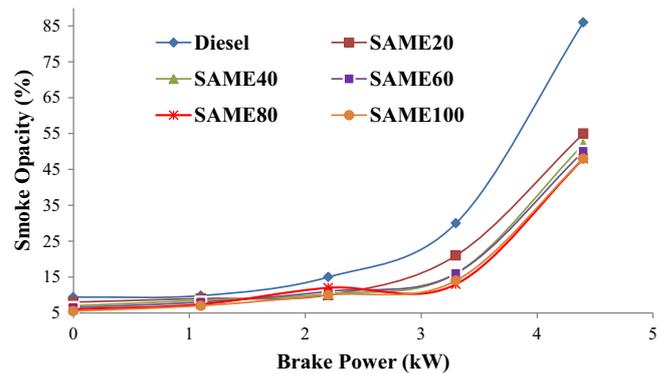


Fig. 10. Variation of smoke density.

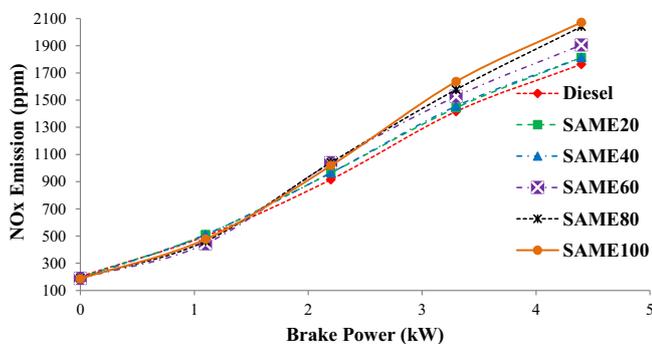


Fig. 9. Variation of NOx emission.

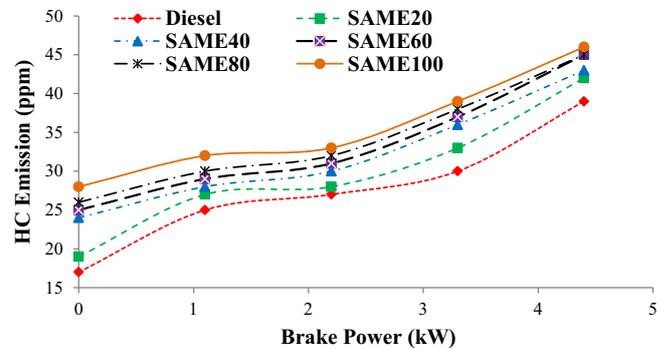


Fig. 11. Variation of UBHC emission.

4.2.2 Smoke opacity

Figure 10 shows the SAME and SAME blends compared to diesel which describe the smoke opacity at different brake power. The smoke opacity of SAME and SAME blends is less than diesel. The viscosity of diesel is less than that of the SAME and SAME blends. The atomization of fuel and spray properties of the SAME and SAME combination can be affected. However, the mixture is lean in oxygen present in SAME and SAME blends and hence the smoke opacity of both the SAME and SAME blends is reduced.

The smoke opacity of SAME and SAME blends is approximately 44% and 40% lower than that of diesel, respectively. The amount of fuel injected increases the BP fuel-air mixture. The SAME and SAME blends provide oxygen to boost the combustion process and reduce fumigation densities compared to diesel.

4.2.3 UnBurnt HydroCarbon (UBHC) emission

In Figure 11, various mixtures display hydrocarbon emissions with diverse brake power. Due to the rich mix, higher BP was observed. The UBHC emissions are found to increase with BP. The UBHC emissions for fuels measured at all loads compared with diesel increase dramatically with different loads and mixtures. SAME and SAME blends UBHC emissions are respectively 17% and 15% higher than diesel.

The rich blend in some places of the combustion chamber increases UBHC emission significantly with higher BP. Since the highest frequency temperature is the highest, the availability of rich combustion mixture due to increased fuel injector quantities into the combustion chamber contributes to UBHC emissions.

4.2.4 CO emission

Figure 12 illustrates the CO emission for various mixtures of different BP. As the ratio of air fuels decreases with a higher BP, CO emissions are increased. The CO emissions are almost the same in all fuels up to 50% of maximum BP and are further lower in the SAME and SAME blends combination than the CO emissions in diesel. Greater unsaturated SAME/SAME blends fatty acids will increase the oxidation process and reduce CO emissions. SAME and SAME blends enhance combustion, oxygen stimulates combustion and decreases CO emissions compared to diesel.

4.3 Performance analysis

4.3.1 Brake thermal efficiency

Figure 13 demonstrates the brake thermal efficiency variance for different test fuels. For the SAME and SAME

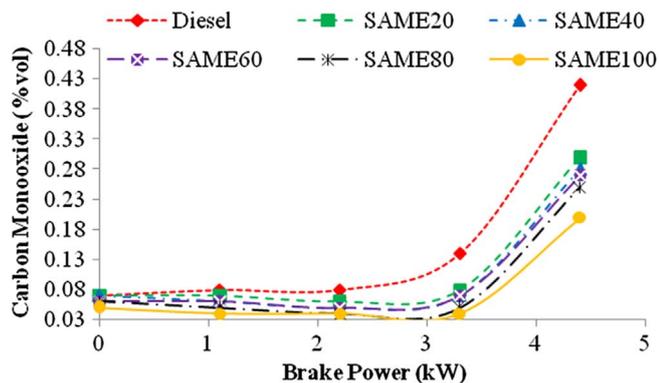


Fig. 12. Variation of CO emission.

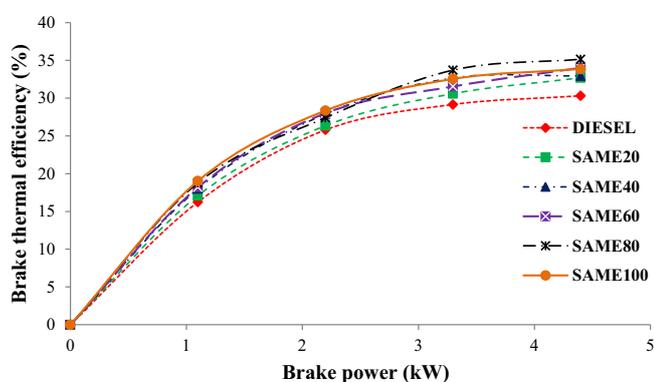


Fig. 13. Variation of brake thermal efficiency.

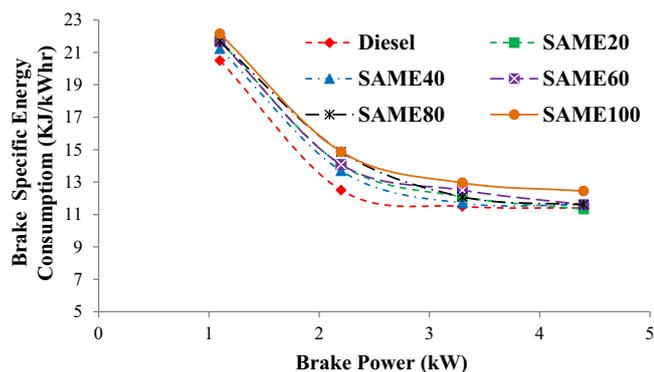


Fig. 14. Variation of brake specific energy consumption.

blends compared to diesel for all of BP, thermal efficiency is slightly higher. For the SAME and SAME blends compared to diesel, the overall improvement in efficiency is 3.38%.

The SAME and SAME blends have shorter ignition delay as the engine is run under advanced injection, combustion starts before TDC. In the vicinity of TDC, maximum heat is released, the highest efficiency is noted. The thermal efficiency is increased near the TDC for SAME and the SAME blends, which induce and deviate from the ideal cycle (Yesilyurt *et al.*, 2020).

4.3.2 Brake specific energy consumption

Figure 14 explains the basic brake specific energy consumption with BP. Specific energy consumption for the SAME reduced up to a part load for SAME blend and diesel and then increases. In all biodiesel blends, the basic energy requirements for diesel are shown to be lower and greater. Since SAME and its mixture have less power than diesel. To produce the SAME power as the heat benefit of the blend, the engine uses more combined fuel than diesel. Due to the decrease in the heating value of a blend the specific energy consumption is rising slowly along with blend percentage (Isik *et al.*, 2020).

5 Conclusion

From the combustion, emission and performance behaviour of diesel, SAME and SAME blends, it is inferred that

- The SAME and SAME blends are equivalent to diesel combustion characteristics.
- In contrast with diesel, SAME and SAME blends indicate decreased CO emission, smoke opacity and slightly higher UBHC emissions.
- The NO_x emission of diesel is lower than the SAME and SAME blends.
- Thermal efficiencies of the SAME and SAME blends are higher compared to diesel and diesel displays with low thermal efficiency.
- SAME demonstrates a drop in smoke opacity above the SAME blends and a marginally high emission of NO_x in a diesel engine.
- Smoke opacity and brake thermal efficiency are found to be the lowest as compared to diesel.
- As fuel for the diesel engine, it is ideal to use the SAME and SAME blends. SAME and SAME blends combinations are also found to be capable of substituting diesel.

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