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Combustion characteristics of crude tyre blends fuel in compression ignition engine

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Abstract

With the rise of automobile vehicles, the number of scrap tyres has been increasing rapidly. Proper management of waste tyre is challenging work for any country. Tyre oil possesses a greater potential of using as a substitute for conventional diesel. The investigation was made on the effects of blends of waste tyre fuel on combustion characteristics such as cylinder pressure (CP), net heat release rate (NHR), cumulative heat release (CHR), ignition delay (IGD), exhaust gas temperature (EGT), and % heat equivalent to brake power (HBP). It was found that crude tyre fuel has a low cetane index which affects the combustion characteristics. The two sample of test fuel were prepared by adding 5% crude tyre fuel to 95% diesel fuel (5BTF) and 10% crude tyre fuel to 90% diesel fuel (10BTF) by volume and their performance and emission characteristics were studied in a single cylinder four stroke diesel engine. For 10BTF, peak CP was reduced by 6.69%, IGD increased by 10.85%, NHR increased by 19.33% and there was a small difference in EGT with diesel. The opacity value of the blends of tyre fuel was found within the emission standard of Nepal. It is concluded that a blend of crude tyre pyrolysis oil up to 5% by volume with diesel shows similar combustion characteristics as that of diesel.

Keywords: Tyre pyrolysis fuel, Ignition delay, Peak cylinder pressure, Heat equivalent to brake power

1. INTRODUCTION:

The extensive use and increase in depletion of petroleum fuel sources have led to the search for alternative fuels for the internal combustion engines. The increasing consumption of petroleum product leads to the shortage of crude oil and there is uncertainty in the crude oil price in the international market which affect the national economy [1] .

These alternate fuels can either be obtained as biodiesel or from the conversion of waste substances to energy. The number of automotive vehicles is increasing day by day. Along with this, the proper disposal of automotive tyres has become a major concern for the community. The improper disposal of these substances presents a major ecological hazard since they are not biodegradable, so disposal is a serious challenge since most landfills do not accept them. There are various alternatives for tyre recycling, which include retreading, reclaiming, incineration, grinding, etc. But these methods have significant drawbacks and limitations. However, pyrolysis can be considered for tyre recycling as a non-conventional method, which is recently gaining the renewed attention.

Presently, waste tyres in the country could be regarded as constituting a menace to human and environmental health [2]. They are found in illegal dumpsites across the country with storm or rainwater and thus constitute a breeding haven for mosquitoes. The major landfilling sites aren't only hampering the quality of land but also creating a harmful effect on human beings as well as on animals. Adverse health outcomes such as abnormalities in liver function, an increased presence of chromosomal changes were reported in the vicinity of a landfill site in Mellery, Belgium [3-5].

Tyre burning is a very attractive short-term option but emits ultra-fine particles that have toxicity all of their own. They burn for the generation of heat by people in factories and brick furnaces. It is widely known that such action will lead to the release of noxious gases such as NOx, SOx, COx, etc. into the atmosphere causing atmospheric pollution. Environmental concern centres on highly toxic additives used in manufacturing, such as zinc, chromium, lead copper, cadmium, and sulphur.

Several studies have been carried out in the production of tyre pyrolysis oil from waste automobile tyres by various techniques [6-8]. Tyre pyrolysis fuel (TPF) characteristics strongly depend on the pyrolysis process characteristics, process temperature and nature of waste automobile tyres used [9]. In thermal pyrolysis, mainly the rubber polymers are heated and decomposed to lower molecular products, such as liquids or gases, which can be useful as a fuel or the chemical source. The yield is 55% oil, 25% carbon black, 9% steel, 5% fibre, and 6% gas, and the maximum yield is obtained at 415 ºC [6]. Tyre pyrolysis oil shows closer property to diesel [10, 11]. The viscosity and sulphur content of crude TPF are the two parameters that influence engine performance and emissions. The high viscosity of the fuel will lead to problems in the long run which include carbon deposit, oil ring sticking, etc. [12].

Table 1: Elemental composition of tyre oil

Tyre samples	Commercial car firestone [16]	Scrap tyre [17]	Truck car [18]	Shredded crumbed tyre [19]	Scrap tyre [20]	Waste tyre [21]	Diesel [11]
C	74.2	86.7	83.2	86.4	85.2	82.8	87.4
H	5.8	8.1	7.7	8	7.3	7.6	12.5
N	0.8	0.4	1.5	0.5	0.4	0.5	0.18
S	1.5	1.4	1.4	1.7	2.3	1.3	0.02
O	4.7	1.3	6.2	3.4	0.5	4.5	0
Moisture	0	0.7	1.4	1.3	1.2	0.8	
Volatiles	58.8	61.9	66.1	62.2	61.3	68.7	
Fixed Carbon	27.7	29.5	27.5	29.4	33.5	27.2	
Ash	13.5	8	5.0	7.1	5.2	3.3	

TPF has lower carbon content than diesel which reduces the calorific value of tyre fuel concerning diesel. Ash content in tyre fuel (TF) is higher than diesel. Higher ash content causes wear in the fuel pump, injector, and piston rings. So, TF should be blend with diesel while using as fuel in the CI engine. The majority of the studies adopted 5–20% blends of waste tube diesel (WTD) fuel with diesel. A diesel engine was able to run up to 70% blend of TPF and 30% diesel [13, 14]. 5% blend of TPF with diesel shows a similar character as that of the diesel [15]. Due to the lower cetane number of TPF, the engine cannot be run with 100% crude tyre oil. There is significant potential for adopting the practice of blending tyre pyrolysis fuel (CTPF) with diesel in Nepal, particularly considering its environmental benefits. Nepal faces challenges in waste management, including the disposal of used tyres. By utilizing waste tyres in the production of CTPF and blending it with diesel, several environmental benefits can be realized. Firstly, this practice reduces the environmental burden of waste tyre disposal, which often leads to open burning, releasing harmful pollutants into the atmosphere. By converting waste tyres into fuel, we not only reduce the volume of waste but also prevent the emission of harmful gases. Secondly, the utilization of CTPF in diesel blends can contribute to a reduction in greenhouse gas emissions. Diesel engines produce significant amounts of carbon dioxide (CO_2), contributing to climate change. By incorporating CTPF, which is derived from a renewable source, into diesel, we can reduce the overall carbon footprint of diesel combustion.

Most of the literature on tyre fuel is focused on the production of refined tyre oil by following the distillation and de-sulfonation method and testing the performance, combustion, and emission characteristics of the blends of distilled tyre fuel with diesel. There is no sufficient work on blends of the crude tyre with diesel on engine performance and combustion. The study aims to investigate the combustion of CI engines when fueled with blends of tyre fuel up to 10% by volume.

2. Materials and Methods

2.1 Crude oil production

The collected tyres were washed with water, the washing tyre was followed by the removal of steel wires and fabrics and is shown in figure 1. The tyres were then sliced into small pieces. The sliced pieces were then washed with water and allowed to feed into the pyrolysis chamber. The pyrolysis chamber was maintained at a constant temperature of 375 ^{0}C. The vapor coming from the pyrolysis chamber is then passed through the condensation chamber. Nitrogen gas (N_2) is feed into the pyrolysis chamber for equal distribution of heat in the pyrolysis chamber. The pyrolysis chamber is heated by a heater placed at the bottom of the pyrolysis chamber. Two temperature sensors are used placed at the top and bottom of the pyrolysis chamber for temperature monitoring. The condensed tyre fuel was collected into two collectors and the non-condensed gases were flared into the atmosphere. The char was collected after cooling the pyrolysis chamber. After collecting crude tyre fuel, two samples of test fuel were prepared by blending 5% crude tyre oil fuel to 95% diesel fuel and 10% crude tyre oil fuel to 90% diesel fuel by volume.

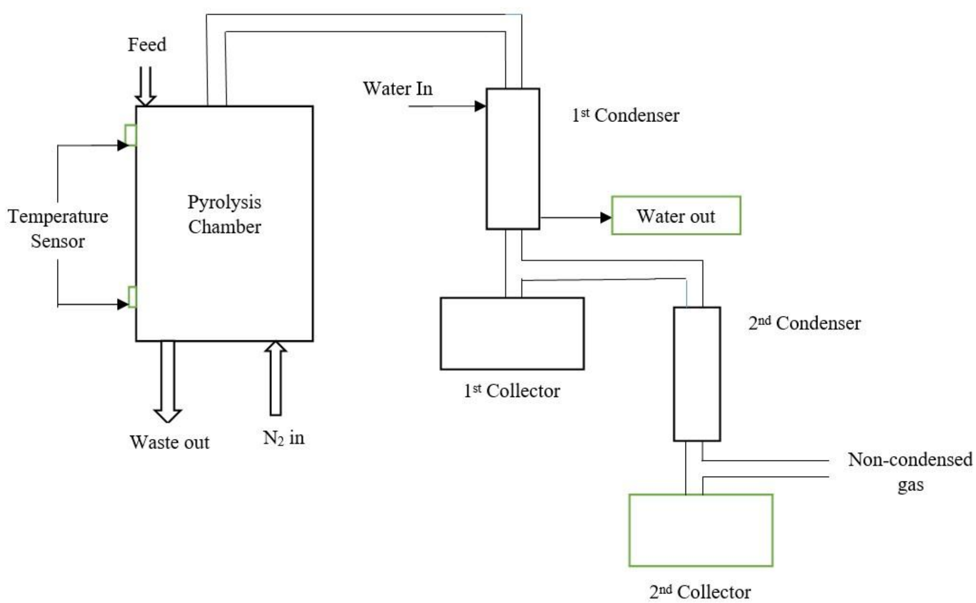

Figure 1: Process diagram of tyre pyrolysis plant

2.2 Experimental Set-up

Table 2: Engine Specification

Type	Single cylinder, four-stroke
Maximum Power	3.50 kW
Cooling	Water
Injection	Direct Injection
Speed	Constant (1500 rpm)
Injection pressure	220 bars
Cylinder Bore	87.50 (mm)
Stroke Length	110.00 (mm)
Connecting Rod length	234.00 (mm)`
Swept volume	661.45 (cc)`
Compression Ratio	17.00
Dynamometer	Eddy Current
Specific Gas Constant (kJ/kgK)	1.00
Adiabatic Index	1.41
Number Of Cycles	10
Cylinder Pressure Reference	0°
Smoothing	2°
TDC Reference	0°

The experiment of three different fuel, i.e. diesel, 5BTF and 10BTF was performed in a Kirloskar test engine at the automobile laboratory of Thapathali Campus. A single-cylinder four-stroke engine generates a maximum brake power of 3.50 kW at 1500 rpm. The engine was coupled with an eddy current dynamometer and speed was maintained constant throughout the test. The pressure sensor was fitted on the head of the cylinder which measures the cylinder pressure and for the exhaust gas temperature reading, a temperature sensor was placed at the exhaust of the CI engine. A schematic diagram of the test engine is shown in figure 2.

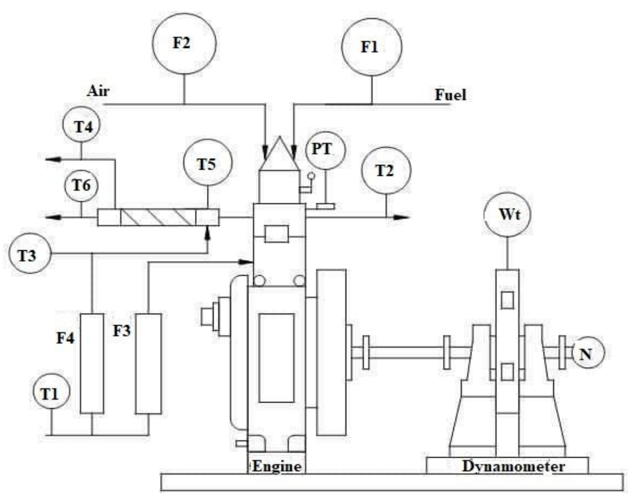

Figure 2: Schematic Diagram of test engine

F_1 = Fuel consumption (kg/hr)
F_2 = Air consumption (kg/hr)

F_3 = Jacket cooling water (kg/hr)

F_4 = Calorimeter water flow (kg/hr)

T_1 = Jacket water inlet temp (°C)

T_2 = Jacket water outlet temp (°C)

T_3 = Calorimeter water inlet temp (°C)

T_4 = Calorimeter water outlet temp (°C)

T_5 = Exhaust gas to calorimeter inlet temp (°C)

T_6 = Exhaust gas from calorimeter outlet temp (°C)

2.3 Opacity meter Specification

Table 3: Opacity meter Specification

Model number:	Opacimeter RTM 430.
Measuring chamber length:	432 mm
Power supply:	via Emissions System Analysis (ESA), Bosch Emissions Analysis (BEA) or Emissions Analysis Tester (EAM)
Application range:	+2 °C to +40 °C
Relative air humidity of ambient air:	< 90 % without thawing
Max. Exhaust-gas temperature at device input:	200 °C
Class of protection:	IP 33 Dimensions: (W x H x D in mm) 594 x 203 x 151
Weight:	approx. 8 kg
Noise emissions:	< 70 dB (A)
Electromagnetic compatibility (EMC):	This product is a Class A product in accordance with EN 5502

2.4 Blending Operation

To mix the tyre fuel and diesel, a volumetric blend was performed in two ratios: 5BTF and 10BTF. The blending process involved shaking the prepared blend for 5 minutes to ensure proper mixing. Once the sample settled, a visual inspection was conducted to verify if the blending was complete. Since the viscosity and density of tyre fuel and diesel are in the same range, volumetric blending was effective in achieving thorough mixing.

3. Results and Discussion

3.1 Fuel Property

Table 2 illustrates the fuel property of crude tyre fuel (CTF). CTF contains heavier hydrocarbon which has a significant effect on the fuel properties of CTF. It is found that the density and viscosity of CTPF are higher than diesel. The high density and viscosity of CTPF affect the fuel atomization and air/fuel mixing. The calorific value of CTPF is lower than diesel which affects the fuel burning and heat release from the combustion chamber. The cetane index of CTPF is lower than diesel which affects the ignition delay and pre-combustion duration in the combustion chamber. The effect of fuel properties of blends of CTPF on the engine is illustrated in the combustion characteristics.

Table 4: Fuel property

Fuel Property	Value	Standard
Density @15 °C	0.8993 g/cm³	ASTM D4052-11
Flash Point PMCC	43°C	ASTM D93-12
Calorific Value	4.23 MJ/kg	ASTM D4868-00
Viscosity @40 ⁰C	3.78	
Distillation Temperature (⁰C)		ASTM D86
IBP	114.2	
10% Recovery	115.2	
50% Recovery	295.8	
90% Recovery	378.2	
FBP	379.5	
Cetane Index	31.13	

3.2 Combustion Characteristics

Ignition delay is a major combustion characteristic of diesel engines. With the rise of load, the ignition delay period decreases for proper and fast burning of the fuel and to counter the higher load demand from the engine. The higher the ignition delay, the higher will be the pre-combustion duration. From figure 3(A), it is found that the rise of blending ratio of TF with diesel increases the ignition delay. This is due to the lower cetane number of CTPF. The figure 3(B) shows the relation of exhaust gas temperature with brake power. It is seen that with the rise of load, the exhaust gas temperature increases for all the tested samples. Exhaust gas temperature of diesel varies from 123.06 °C at low load to 300.87 °C at high load, for 5 BTF varies from 136.93 °C at low load to 299.65 °C at high load and 136.27 °C at low load to 298.19 °C at high load for 10 BTF. Exhaust gas temperature of blends of tyre oil was found higher than that of diesel except at high load where there is marginally small difference in exhaust gas temperature of blends of tyre oil and diesel, this because tyre oil having lower cetane number.

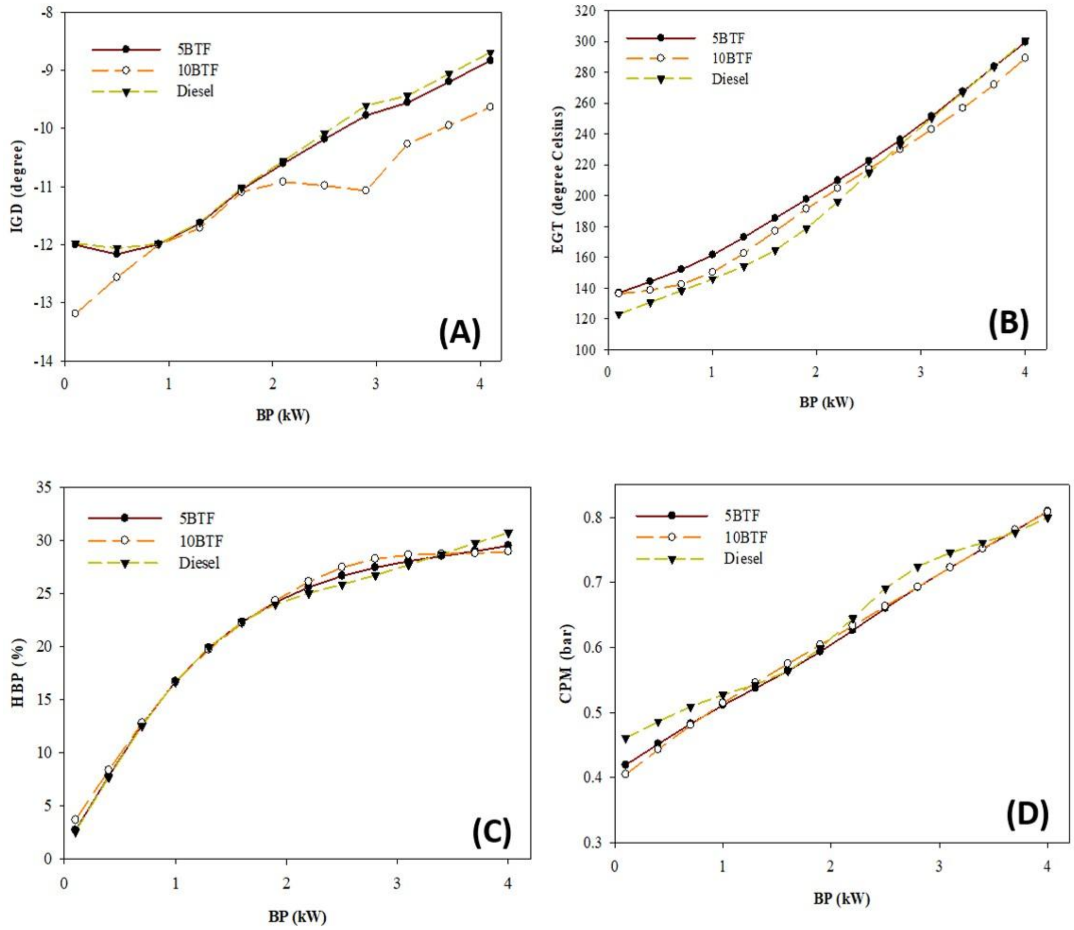

Figure 3: Relation of brake power with ignition delay time (A), exhaust gas temperature (B), heat equivalent to brake power (HBP) (C) and cylinder pressure (D) of different fuel samples

From the first law of thermodynamics, it is observed that heat produced in the combustion chamber converts into useful work i.e. heat equivalent to brake power, heat loss in jacket cooling water, heat loss in the exhaust, and unaccounted heat which is also called heat lost in radiation. Heat equivalent to brake power can be regarded as the brake thermal efficiency of the engine. With the rise of load, heat equivalent to useful work increases. From figure 3(C), it can be seen that the higher heat equivalent to brake power (HBP) of diesel varies from 2.58% at low load to 34.38% at high load, 2.68% at low load to 29.47% at high load for 5 BTF, and 3.66% at low load to 28.91% at high load for 10 BTF. Higher Heat equivalent to brake power is preferred. From figure 6, it can be found that. There is a small margin of difference in the % HBP of diesel and 5BTF throughout the load but the %HBP of diesel is higher than 10 BTF except at high load. Blends of tyre oil have lower %HBP, this is because of the lower calorific value and lower oxygen content. Similarly, figure 3(D) shows the relation of maximum cylinder pressure with brake power. Figure illustrates that the maximum cylinder pressure for all tested samples with load. Blends of tyre fuel have lower cylinder pressure than diesel, this is because of lower calorific value and lower oxygen content of blended fuel.

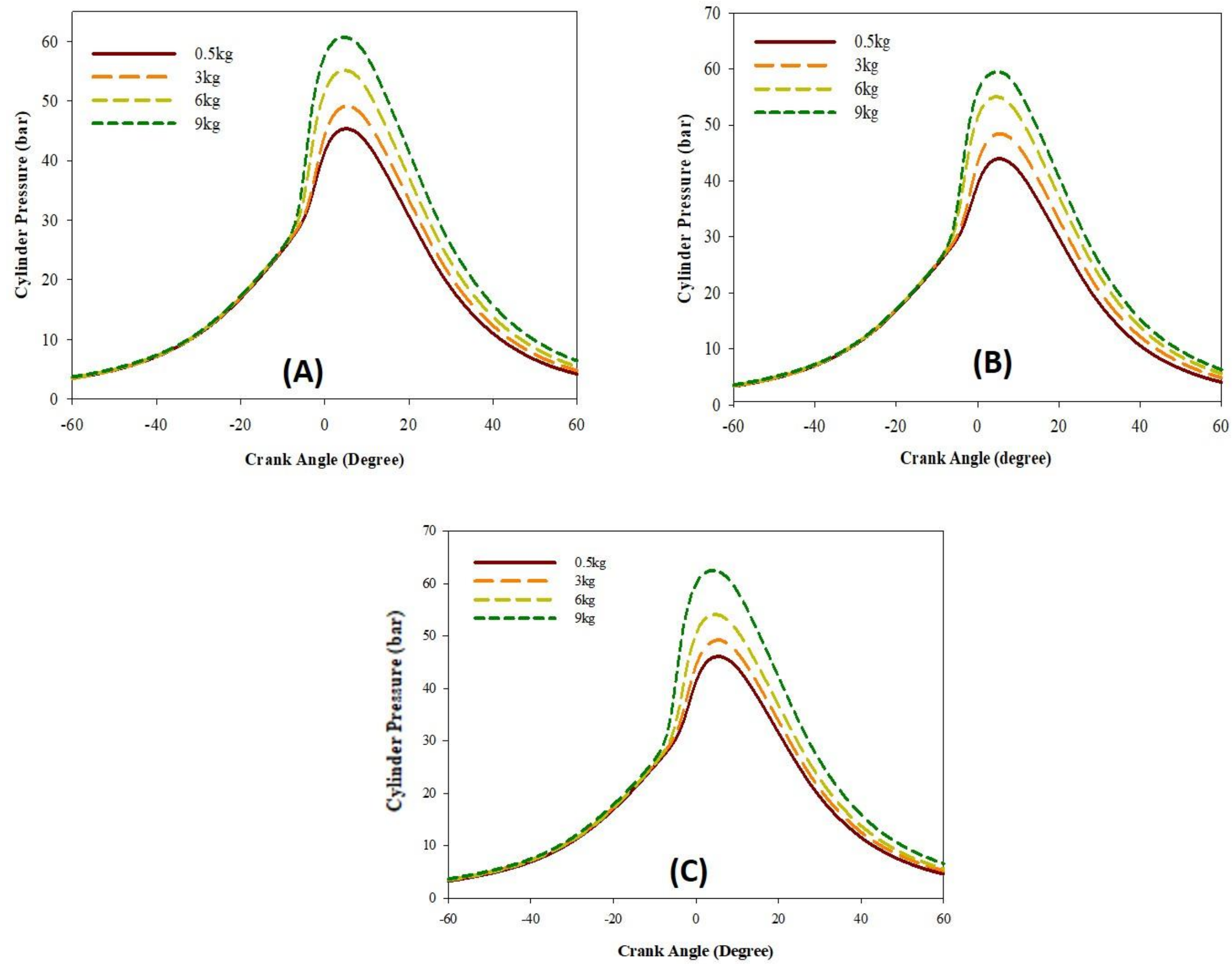

Figure 4: Cylinder Pressure with Crank angle of 5 BTF (A), 10 BTF (B) and diesel (C)

Relation of cylinder pressure with rising of crank angle of 5 BTF, 10 BTF, and diesel are shown in figure 4(A), 4(B) and 4(C). From these figures it can be seen that with the rise of load, cylinder pressure increases. Maximum cylinder pressure is the pressure exerted on the burning of fuel to the piston of the cylinder. From figure 6, it can be seen that the maximum cylinder pressure of diesel varies from 45.54 bar at low load to 66.38 bar at high load, i.e. for 5 BTF varies from 44.85 bar at low load to 66.38 bar at high load, and for 10 BTF varies from 43.15 bar at low load to 68.96 bar at high load. Cylinder pressure of diesel was found higher than that of blends of tyre fuel, this is due to shorter ignition delay of diesel in comparison to other blends of tyre fuel.

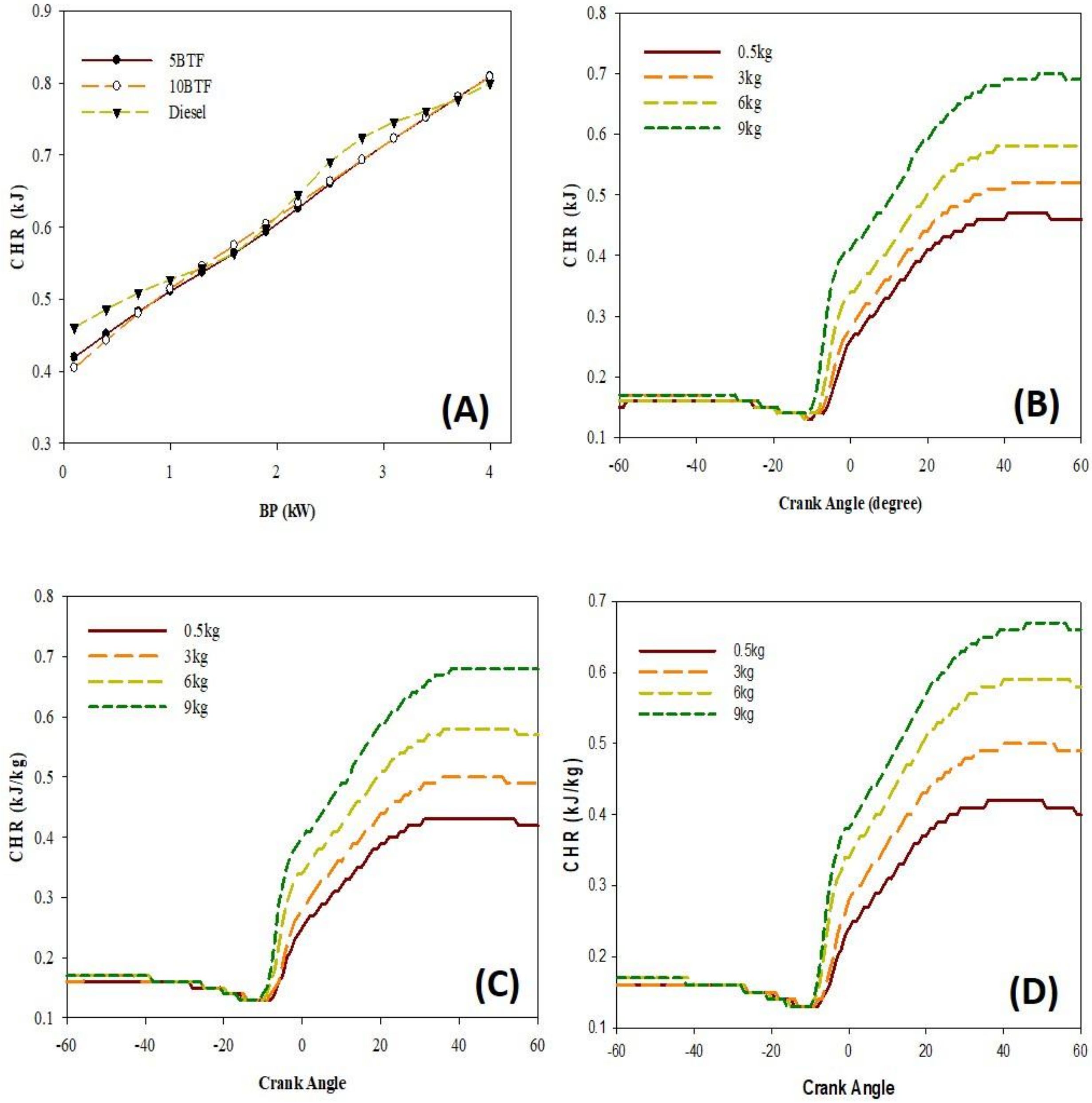

Figure 5: Relation of cumulative heat release with brake power of all samples (A), cumulative heat release with crank angle of diesel (B), 5BTF (C) and 10BTF (D)

CHR is the sum of consecutive heat releases of every crank angle. Cumulative heat release of all samples with BP, cumulative heat release with crank angle of diesel, 10 BTF, and 5 BTF are shown in the figure 5(A), 5(B), 5(C) and 5(D) respectively. From figures, it can be seen that cumulative heat release of diesel varies from 0.46 KJ at low load to 0.80 KJ at high load, 0.42 KJ at low load to 0.81 KJ at high load for 5 BTF and 0.40 KJ at low load to 0.81 KJ at high load for 10 BTF. Here, diesel has a higher cumulative heat release than the blends of tyre oil. This is due to the lower calorific value of blends of tyre oil compared to diesel. The density and viscosity of diesel are comparatively lower than the blends of tyre oil, which leads to the better diffusion of the air/fuel mixture. At the beginning of the combustion, negative cumulative heat release is observed, this is due to the effect of fuel accumulate in the combustion chamber before the start of combustion.

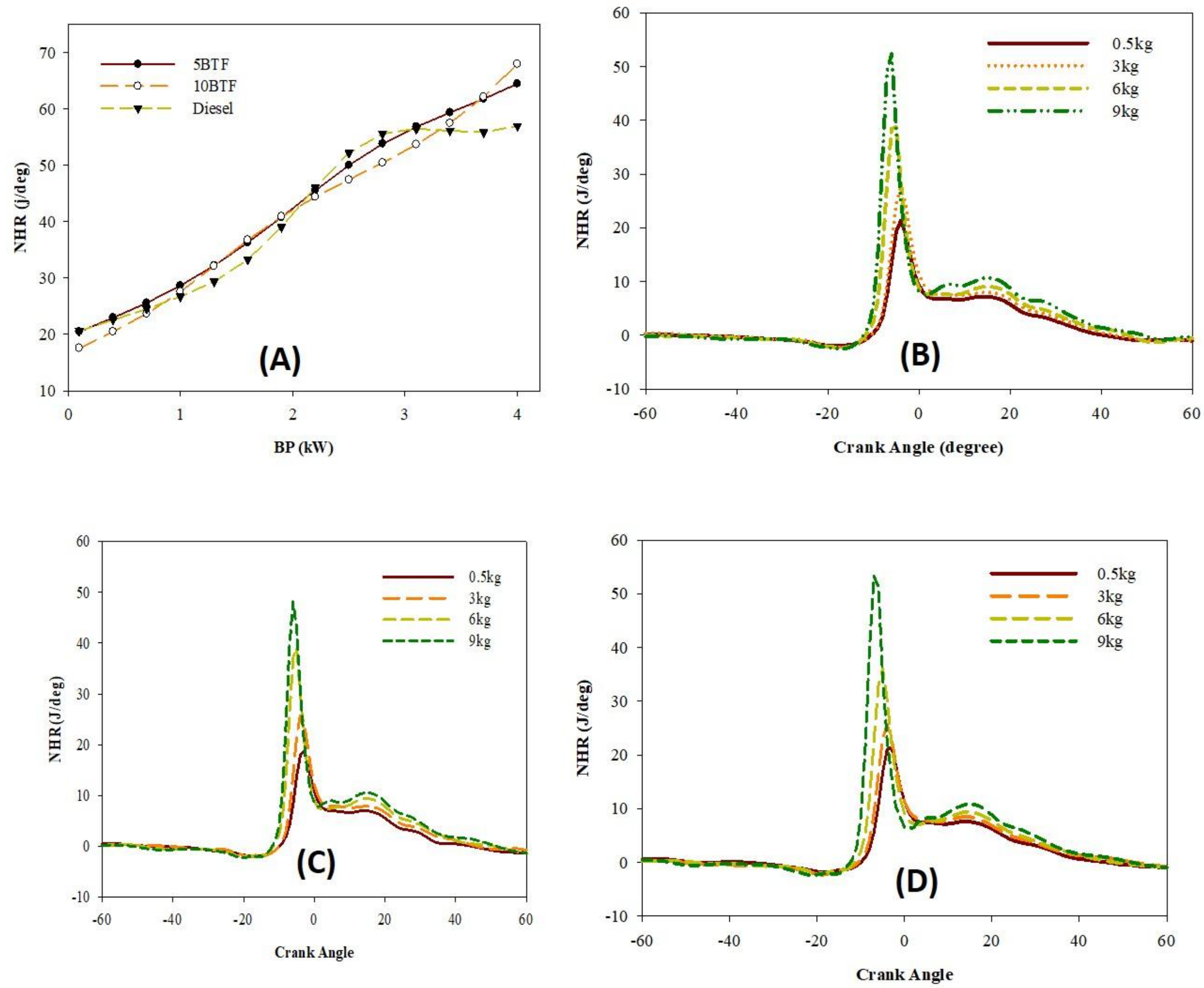

Figure 6: Relation of net heat release with brake power of all samples (A), net heat release with crank angle 5BTF (B) and 10BTF (C) and diesel (D)

Net heat release of 5 BTF, 10 BTF, and diesel with crank angle are shown in the figure 6(B), 6(C) and 6(D) respectively. From figures, it is illustrated that at low load, net heat release of diesel is found higher than the blends of tyre fuel. With the rise of load, NHR of blends of tyre fuel increase more rapidly than diesel, this is due to lower cetane number of tyre oil, increases the ignition delay of blends of tyre oil. An increase in ignition delay increases the pre-combustion duration and leads to an increase in NHR of blends of tyre oil. From experiment showed that the net heat release values of diesel, 5BTF and 10BTF were found from 20.60

J/deg at low load to 56.98 J/deg at high load, 20.46 J/deg at low load to 64.46 J/deg at high load and 17.56 J/deg at low load to 67.99 J/deg at high load respectively.

3.3 Emission Characteristics

As per the emission standard, the opacity value for diesel is maximum 2.44 m^{-1}. The opacity value of diesel, 5BTF and 10BTF was found to be 2.12, 2.18 and 2.3 respectively. It was found that the opacity value of blends of tyre fuel goes on increasing with the rise of the blending ratio because of the presence of impurities in the tyre fuel.

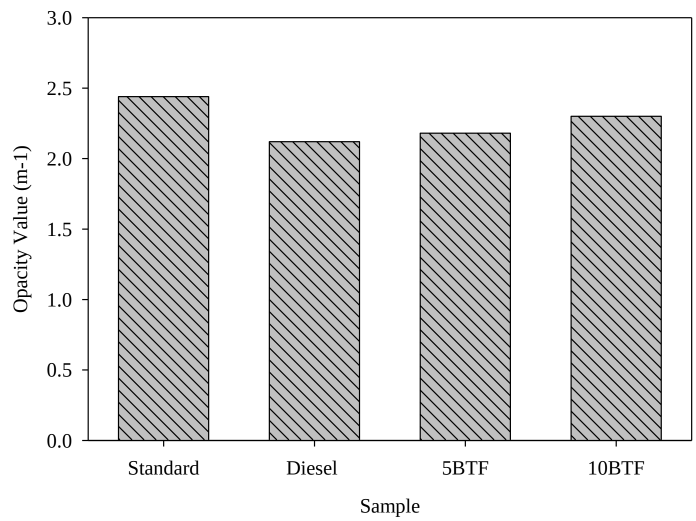

Figure 7: Relation of opacity value with various fuel

4. Conclusions

The test has been performed on the blends of CTPF with diesel up to 10% by volume on the CI engine. It has been shown that 5BTF shows has similar combustion characteristics as that of diesel. The conclusions of the research on blends of tyre pyrolysis fuel with diesel are mentioned below:

- The ignition delay of 10% CTPF blend (10BTF) was higher than that of diesel, while the difference in ignition delay between diesel and 5% CTPF blend (5BTF) was minimal.
- Peak cylinder pressure increased by 2.71% for 5BTF and 6.69% for 10BTF compared to diesel.
- Heat equivalent to brake power decreased by -3.94% for 5BTF and -5.75% for 10BTF, indicating alterations in fuel properties.
- NHR increased by 13.12% for 5BTF and 19.33% for 10BTF, suggesting enhanced combustion efficiency.
- A minor difference in exhaust gas temperature was observed between 5BTF and 10BTF.
- Cumulative heat release increased by 1.20% for 5BTF and 1.09% for 10BTF, indicating improved energy release.

- The opacity value increased with the rise of the blending ratio for tyre fuel blend.Peak cylinder pressure of 5BTF and 10BTF increases by 2.71% and 6.69% respectively.

Limitation

The emission characteristics of diesel vehicles cannot be directly measured due to the unavailability of a diesel gas analyzer in the laboratory of Nepal. Instead, the referred test for diesel vehicles in Nepal is the opacity test, which measures the amount of light blocked by emissions. However, this opacity test provides an indirect assessment of emissions and may not capture the full spectrum of pollutants emitted by diesel vehicles.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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