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Experimental and numerical assessment of the rotary bed reactor for fuel-processing and evaluation of produced oil usability as fuel substitute

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ABSTRACT

In current work, waste tires recycling using pyrolysis was performed inside a rotary bed reactor without oxygen-producing oil, black carbon, and synthetic gas. In that respect, CFD analysis was applied using ANSYS software to design the reactor and test its material resistance to the temperature rise. Thermal and mechanical stresses were evaluated to find an acceptable reactor design. Pyrolysis of tires to oil was performed at a temperature of 420 °C. Tire and diesel oils blends of 5, 10, and 20% volume percentages were prepared for experimentation. Tire oil blends properties were close to crude diesel. Characteristics of combustion, performance and emissions of diesel engines that used tire oil blends were investigated compared to crude diesel. The thermal efficiency maximum decrease of TO20 was 21% in comparison to pure diesel. The maximum increases in CO, smoke, and HC emissions of TO20 were 35, 20, and 25% compared to diesel fuel, respectively. The highest decline in NOx emission of TO20 was 19% related to crude diesel fuel. Oil blends achieved the higher peak cylinder pressures about diesel fuel. In conclusion, lower volume percentages of up to 20% of tire and diesel oil blends are recommended to be used without any engine modifications.

Nomenclatures

ASTM	American Society for Testing and Materials
BSFC	Brake specific fuel consumption, kg/kW.hr

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BTE	Brake thermal efficiency, %
CO	Carbon mono oxide emission, %
D100	Pure Diesel Oil
EGT	Exhaust gas temperature, ^0C
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatography Spectrometry
HC	Unburned hydrocarbon emission, ppm
HRR	Heat release rate, Joule/Degree
LHV	Lower heating value, $MJ \cdot kg^{-1}$
m_f	Fuel flow mass, $g \cdot s^{-1}$
NOx	Nitrogen oxides emission, ppm
P_e	Engine Brake power, kW
T	Engine Torque, Nm
TO5	Blend of tire pyrolysis oil 5% and diesel oil 95% by volume
TO10	Mixture of tire pyrolysis oil 10% and diesel oil 90% by volume
TO20	Blend of tire pyrolysis oil 20% and diesel oil 80% by volume
TO100	Tire pyrolysis oil
ω	Angular velocity, s^{-1}

1. Introduction

The continuous increment of energy consumption, conventional oil depletion, and the need for a sustainable source led to a search for fuel substitutes [1]. The economical alternative, such as waste tires, consists of hydrocarbons directly converted to gas, liquid oil, and solid char by pyrolysis. Waste tires disposal is a huge problem all over the world [2]. The disposal of waste tires leads to a fire risk and toxic emissions [3]. Oil extraction from waste tires as an alternative fuel is one of the possible ways to overcome this problem [4]. Waste tires conversion to energy represents a cleaner fuel and carbon source for crude oil [5]. The waste tires were heated in a pyrolysis bed reactor at temperatures ranging from 425 to 575 °C. At a heating temperature of 475 °C, waste tires pyrolysis yielded 58.2% of the oil and a higher limonene percentage [6,7]. Natural zeolite and lime at different weight ratios were added to improve the waste tire pyrolysis oil properties. Light products were produced from pyrolytic oil distillation. Fuel sample with a lime mixture of 10% mass percentage showed the optimum distillation temperature near crude diesel [8–10]. These mixtures were classified into heavy and light constituents according to their distillation points which are named GLF (Gasoline Like Fuel) and DLF (Diesel Like Fuel) [11–13]. Tire oil blends have less oxygen content, cylinder combustion temperatures, and all these lead to NOx formation increases with the oil percentage increase [13–16].

The particle size affects the waste tyres pyrolysis to determine the overall energy extent and pyrolysis reaction time [17–21]. The optimized particle size in different heating approaches was considered [22–24]. The pyrolysis process converted the waste tires at a temperature of 300 °C to oil to particulate carbon black of polymeric shell surface and constituted by bound rubber [25–27]. The size of the carbon black particle was about 22 nm, and the thickness of the rubber shell ranged from 7 to 12 nm [28–30]. Tire pyrolysis oil was mixed with diesel fuel as 10, 15, and 20% by volume. The concentration of 15% produced less fuel consumption than 10 and 20% by volume percentages [31]. The tire pyrolytic oil viscosity is higher than diesel fuel [32,33]. At part load, BSFC of 75% tire oil is the lowest while the thermal efficiency is the highest [34]. As the mixture concentration increases, the brake thermal efficiency decreases. The increase in the blend percentage resulted in the specific fuel consumption increase. Oil blends produced higher exhaust gas temperatures than diesel oil [35]. The concentrations of HC and CO of oil mixtures were higher, but the NO_x emissions were lower than diesel oil [36].

Operation of engine with concentrations of tire oil from 10 to 50% led to the injector clogging because of the oil's higher viscosity. Tire oil mixtures showed higher hydrocarbons emissions compared to diesel oil. Tire oil of 10% oil percentage exhibited an increase in HC emission up to 3%. CO emission was higher for tire oil blends. A rise of 0.5% in NOx emission was shown for 10% oil concentration [37]. BSFC of plastic oil blends was higher compared to crude diesel. Plastic oil blends up to 20% showed higher brake-specific fuel consumption for diesel oil [38,39]. Volume percentages of 10, 20, 30, and 40% of oil mixtures had been tested. There were increases in CO emissions for tires rubber oil blends except for the 20% blend ratio reduced by 15% [40,41]. HC emissions were decreased for tire pyrolysis oil blends about pure diesel. CO_2 and NOx emissions were decreased for different TPO blends [42,43]. There was an increase in thermal efficiency of 50% tire oil volume percentage compared to diesel oil. NOx concentrations values for 50 and 75% of tire pyrolysis oil percentages were lower than diesel oil. Carbon monoxide and nitrogen oxides emissions were higher for TPO compared to diesel oil. Smoke emission was higher for tire pyrolysis blends [44,45]. Brake thermal efficiencies of oil blends were higher at related to crude diesel. Carbon monoxide and hydrocarbons emissions of waste plastic oil were higher [46]. BTE of TPO of 25% percentage was lower than diesel fuel [47]. Tire oil blends of 10, 20, and 30% percentages were prepared on a mass basis. The thermal efficiency of oil blends was decreased compared to diesel oil. CO emissions decrease, and NO_X emissions increase associated with the oil percentage increase [45,47].

Based on the previous studies, it is possible to say that most of the literature papers related to the oil production from waste tires, and then the papers generally focused on the emissions and performance characteristics of the internal combustion engines burning the blends of tire oil and binary diesel fuels. However, the previous studies did not mainly deal with the details of oil production stages, but the details of oil production were handled in the present paper. An oil pyrolysis unit was designed and manufactured in this study. Furthermore, the influences of thermal stresses on the oil reactor were analyzed using CFD analysis. Since the tire wastes represent a hazard source, the paper concentrated on the problem solution of the waste tires disposal for the governments. Accordingly, this work aims also to design and manufacture a suitable rotating bed reactor equipped with a water condenser producing the oil from waste tires. Waste tires were heated up to convert them into liquid oil and black carbon.

Additionally, the produced oil was characterized using FTIR and GC analysis. TO blends of 5, 10, and 20% volume percentages were blended into the conventional diesel fuel because of higher percentages' higher viscosity and density. The chemical and physical properties of the tire oil mixtures were evaluated according to ASTM standards in the study. Then performance, combustion, and emission characteristics of the diesel engine fueled by TO blends were comprehensively discussed and compared with those of conventional diesel fuel.

2. Methodology

The experimental work is mainly divided into waste tire oil production and oil test in a diesel engine. Pyrolysis is a renewable technology for recycling waste tires and plastic by thermal chemical decomposition without oxygen. The main products of tire and plastic pyrolysis were crude oil and black carbon. The used waste tires mass was of 10 kg weight. The pyrolysis process was done in a designed rotating reactor at 400–450 °C using nitrogen as an inert gas. Pyrolysis time was 120 min. The reactor was used for heating and melting waste tires. Therefore, CFD analysis was performed using ANSYS 18.1 to test the resistance of the reactor material to the temperature rise. Thermal and mechanical stresses were calculated to find the excellent design of the reactor.

Moreover, the shell and tube condenser was designed with many paths and tubes to condense the oil vapor. The developed system included a tire shredder with 20 cutters to cut the tires into pieces with definite sizes. All designed parts were installed over a prepared, tested bed with a water supply and heat source [24,25].

The rubber was softened after the rubber polymers disintegrated into smaller molecules. The produced vapors can be used directly or condensed to liquid oil. The minerals in the tires are about 40% by weight and were removed as a solid. Finally, the oil was chemically treated and used as an alternative fuel. The reactor was purged by flowing nitrogen gas for 3 min to eliminate the inside air. Nitrogen gas was used to sweep away the produced vapor towards the condenser. The pyrolytic vapor was condensed through the condenser pipes. The reactor heat source and nitrogen supply were switched off, and the decomposition was completed. The reactor temperature was decreased to get the black carbon. The crude oil was preheated up to 100 °C to remove the moisture. Hydro sulfuric acid H_2SO_4 of 8% concentration was blended with the pure oil and well stirred, and then the blend was left for about 40 h in the desulfurization process to reduce the sulfur content. After that, the mixture was separated into two layers. A distillation process separated the heavier and lighter hydrocarbons. The crude oil was on the top, and sludge was on the bottom [26–28].

2.1. Oil pyrolysis unit design

The reactor has a cylindrical shape with an inner diameter, thickness, and a chamber length of 50, 0.3, and 60 cm, respectively. The reactor capacity was designed for producing a volume of 200 L of the produced oil. The reactor dimensions were chosen based on the waste tires mass. This reactor was equipped with baffles inside to cause uniform heat distribution. The reactor was equipped with instrumentation to control the inside temperature and rotating speed. The electrical motor was used to rotate the cylindrical reactor at 3 rpm from a reduction speed gearbox of 70:1 ratio. The pyrolysis system is shown in Fig. 1. The thermal stress that occurred on the outer reactor surface was provided by three-dimensional CFD analysis. CFD analysis gave us the optimal reactor design, which offered the minimum thermal and mechanical stresses at different operating temperatures of 200, 500, 700, and 1000 °C. The maximum deformation was shown in the area of the reactor ends, which were exposed to high thermal stresses.

The thermal expansion of the reactor body was determined due to the heat energy coming out from the burner as the axial thermal

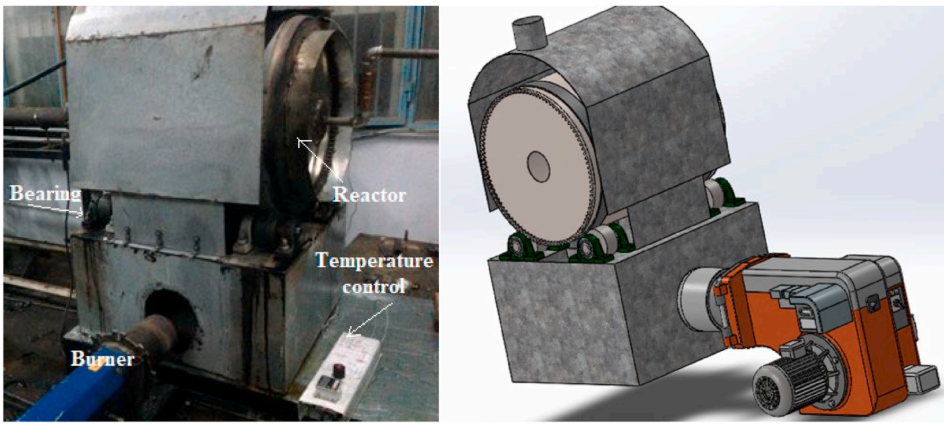


Fig. 1. Pyrolysis system.

expansion. The reactor is installed on four supporters, which touch the reactor via a ring of 3 mm thickness welded to the outer surface of the reactor. This ring is a roller touching the supporters. The expansion should be taken into consideration while designing the rollers and the supporters. Fig. 2 (a, b, and c) shows the proper installing of the rollers and supporters without thermal expansion. The thermal expansion was calculated using a static structural module. The reactor and supporters' geometry were simplified to make the simulation as simple as possible to save time while running the solution. The reactor dimensions are (length = 60 cm and diameter = 50 cm) while the material of the reactor and rollers is stainless steel 310S grade and the supporters' material is stainless steel 37 grade. The reactor side would be fixed, and the other side would be free due to the expansion under thermal conditions, as shown in Fig. 3. The deformation in length should be divided by 2 to get the real deformation on each side of the reactor. The freedom to expand on both sides is just like a solid bar, and the fixation was made to simplify the model solution. Thermal condition variation is due to the used burner and the generated temperature. The reactor temperature must be adjusted at 500 °C, so the thermal conditions were entered as a boundary condition variation at 200, 500, 700, and 1000 °C. The ambient temperature was set to be 22 °C. The deformations in one side are 0.71375, 1.91675, 2.71685, and 3.17 mm at 200, 500, 700, and 1000 °C. Fig. 4 shows the typical deformation plot on the outer reactor surface at different temperatures.

The condenser is a heat exchanger to condense the oil vapor and convert it to a liquid phase. The shell and tube heat exchanger is used to produce a higher heat transfer coefficient than parallel flow. The copper material condenser was 628 mm in length, 12.5 mm in diameter, and 3 mm wall thickness with a heat transfer coefficient of 410 W/m^{2}°C. Inlet and outlet temperatures of the condenser were recorded using a thermocouple of type k. The cooling water passed at a flow rate of 0.02 kg/s, entered the system at 25 °C and left at 35 °C. The condenser rejected thermal load was calculated by heat balance as 84 Watt. The pressure of cooling water is 1 bar. The reactor and condenser designs are shown in Fig. 5.

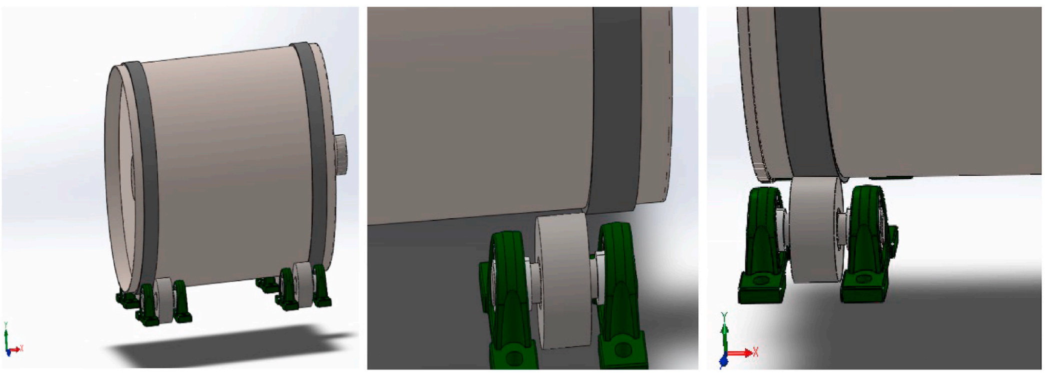
2.2. Tire oil blends preparation

The chemical composition of pyrolysis tire oil was characterized by GC-MS, as indicated in Table 1. The peaks were shown on the mass spectrum range from retention time of 3.06–20.5 min. The highest peak (15.1) was shown at a retention time of 5.9 min. O-Cymene and Benzene, 1, 2, 3, 4-tetramethyl were the main constituents in tire pyrolysis oil. Table 1 shows the GC-Mass analysis of TO. Fourier Transform Infrared Spectroscopy (FTIR) analysis presents the analysis of the inorganic and organic compounds. The functional groups in tire pyrolysis oil show aromatics and aliphatic. FTIR analysis of TO is shown in Table 2. The amines, alkenes, alkanes, phenyl rings, and aldehydes are shown in the FTIR analysis.

TO was blended with crude diesel as 5, 10, and 20% by volume (TO5, TO10, and TO20) because its properties are near diesel oil. At higher percentages of tire oil, the density and viscosity are higher, but the calorific value is lower than diesel oil. The heating rate of tire oil was affected by the reaction time, oil yield, and oil quality. As the temperature was maintained at 450 °C, the hydrocarbons blend depends on the waste material composition. The density of tire oil was higher than diesel oil. Viscosity and flash point of tire oil blends are higher than diesel fuel. Calorific value and cetane number of tire oil were lower than pure diesel. Tire oil sulfur content was evaluated as 1.2%, but after desulfurization, it was reduced to 0.4%. The iodine value gives the measure of the unsaturation degree of a lipid. The higher iodine value leads to the greater number of (C = C) double bonds. Iodine value is directly proportional to the degree of unsaturation (double bonds). The iodine values of diesel and tire oils are 20.5 and 1.9, respectively. Kinematic viscosity, density, lower heating value, and flash point were measured related to diesel fuel, as shown in Table 3.

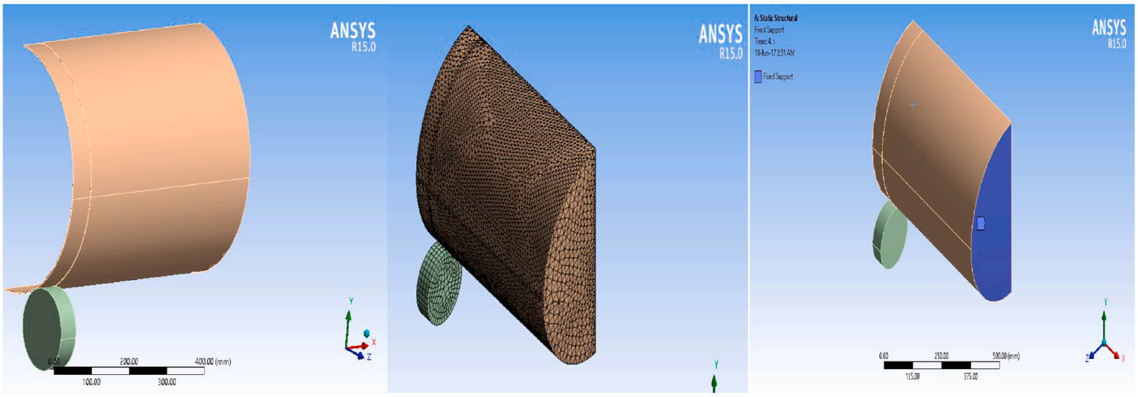
2.3. Engine test rig

Performance, emission, and combustion characteristics were evaluated related to diesel fuel. Fig. 6 shows the experimental setup schematic diagram. The used engine technical specifications are shown in Table 4. The test engine was connected to an AC generator with the maximum output power of 5.7 kW to evaluate the output power. To remove the engine airflow pulsations, the intake air flow rate was calculated using a sharp-edged orifice on the side of the airbox. The pressure drop across the orifice was measured using a U-tube manometer. Type K temperature thermocouple was used to measure the air intake and exhaust gas temperatures. The exhaust



(a) Reactor shape without thermal expansion (b) Wrong installation of the roller and supporter (c) Right installation of roller and supporter.

Fig. 2. Installation of the rollers and supporters with thermal expansion.



(a) Reactor and Supporters geometry. (b) **Fixed side in the thermal expansion**

Fig. 3. The expansion under thermal condition.

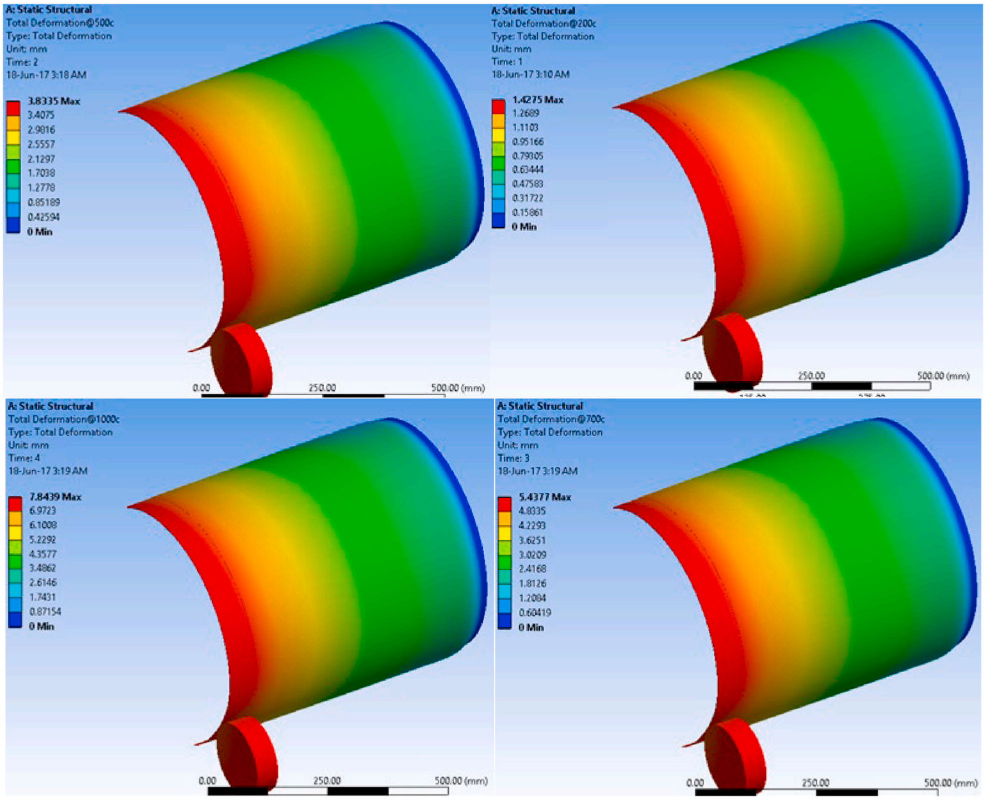


Fig. 4. Reactor body deformation at different operating temperatures of 200, 500, 700, and 1000 °C.

concentrations of CO, HC, NO_X, and smoke opacity were measured using an MRU DELTA 1600-V gas analyzer and an OPA 100 smoke meter, respectively. A Nexus charge amplifier (2692-A-0S4) was connected to a water-cooled piezoelectric pressure transducer (Type: Kistler, model 601A).

The piston top dead centre position was evaluated using a proximity switch of LM12-3004 PA type. The measurements were transmitted to LABVIEW software using a data acquisition card (NI-USB-6210). The engine tests were conducted at 1500 rpm rated engine speed and the range of engine loads from zero to maximum. A diesel engine was operated for 15 min with diesel fuel to reach the steady-state condition. All the experiments were performed with three replicates. R^2 is statistical, representing the proportion of the variance of the dependent variable, which is explained by the independent variable. It is a goodness of fit measure for linear regression models. In all figures, square R is greater than 0.75.

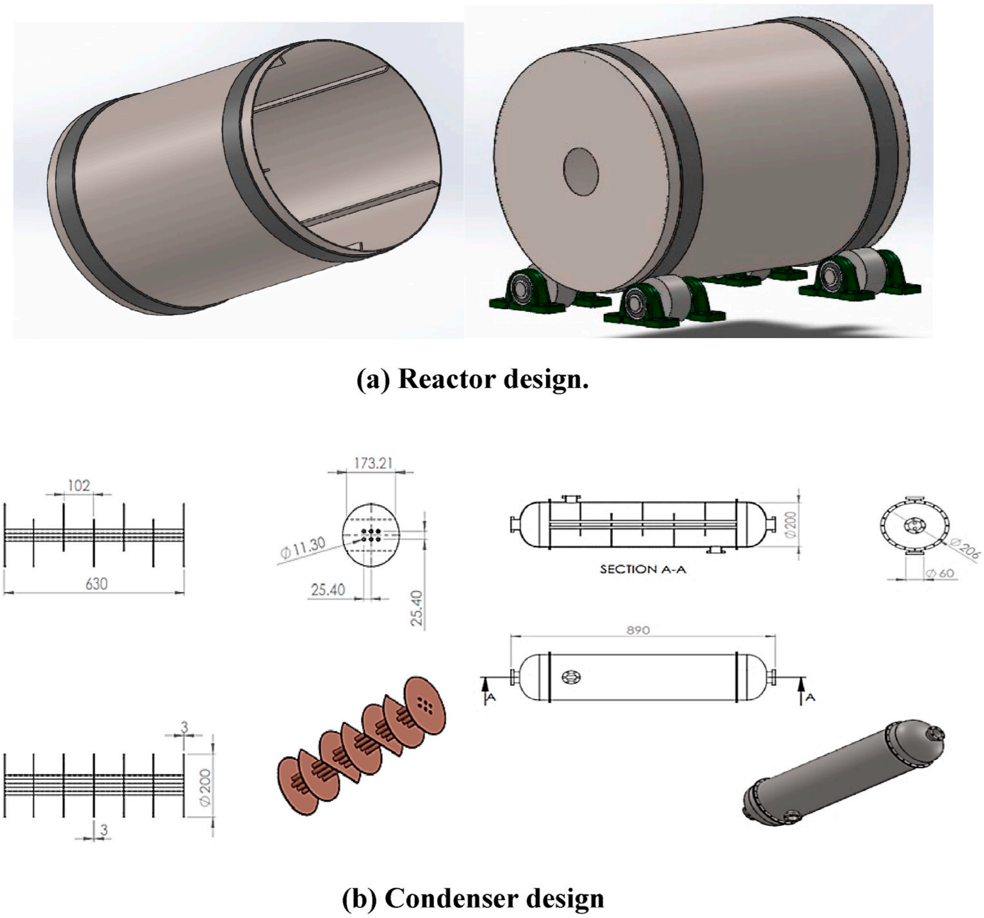


Fig. 5. Schematic diagram of the reactor and condenser designs.

Table 1
GC-Mass analysis of TO.

RT (min)	Compound name	Area, %	Molecular formula
3.06	1-Ethyl Metycylcohexane	0.95	C_9H_{18}
3.3	p-Xylene Benzene, 1,3-dimethyl	4.8	C_8H_{10}
3.4	Propyl cyclohexane	1.05	$C_6H_{11}CH_2$– CH_2CH_3
3.8	M-Ethyl methyl benzene	1.03	C_9H_{12}
4.3	Decane	3.40	$C_{10}H_{22}$
4.8	Benzene	6.22	C_9H_{12}
5.2	Benzonitrile	2.1	C_6H_5CN
5.9	Benzene, 1,2,3,4-tetramethyl, o-Cymene	15.1	$C_{20}H_{26}O$, $CH_3C_6H_4CH(CH_3)_2$
6.02	D-Limonene	5.14	$C_{10}H_{16}$
7.4	Dodecane	2.5	$CH_3(CH_2)_{10}CH$
10.5	1H-Indene, 2,3-dihydro-1,1,5-trimethyl	2.22	C_9H_8
12.3	Naphthalene, 2,7-dimethyl	3.5	$C_{10}H_8$, $C_{10}H_6(CH_3)_2$
12.4	Quinoline, 4,8-dimethyl	4.4	C_9H_7N, $C_{11}H_{18}$
13.4	Naphthalene, 2,3,6-trimethyl	4.5	$C_{10}H_8$, $C_9H_{12}O$
15.9	n-Hexadecane	3.3	$CH_3(CH_2)_{14}$ CH_3
17.9	Octadecane	2.4	$C_{28}H_{58}$
20.5	Tetracosane	1.2	$H(CH_2)_{24}H$

3. Results and discussions

In the present paper, the oil from waste tires is initially obtained from the tire chips in the rotary bed reactor, and then this waste-product oil is volumetrically blended into the conventional diesel fuel at 5, 10, and 20%. Then the waste tire pyrolysis oil-diesel fuel blends are tested on a single-cylinder diesel engine. To better compare and understand the impacts of waste tire pyrolysis oil usage in diesel engines. Therefore, the reference data is gathered. During the experiments, the crankshaft engine speed is constant at 1500 rpm,

Table 2
FTIR analysis of tire pyrolysis oil.

Wavelength Frequency (cm^{-1})	Functional groups
700–810	C–H bend (Alkenes)
850–1040	C=C stretch (Alkenes)
1210–1310	C–S stretch (Amines)
1370–1580	C–H bend (Alkanes)
1615–1820	C=C stretch (Aromatic)
1900–2145	C=H (Phenyl ring)
2245–2610	C–H stretch (Aldehydes)
2710–2935	C–H stretch
2980–3020	C=H bend
3075–3149	C=C stretch (Alkenes)

Table 3
Properties of tire oil blends in comparison to diesel oil.

Properties	Method	Diesel oil	Tire oil (TO100)	TO5	TO10	TO20
Density at 15 °C, kg/m^3	ASTM D4052	835	990	838	842	850
Kinematic viscosity, cSt, at 40 °C	ASTM D445	2.5	15	3	3.5	4.2
Flashpoint, °C	ASTM D93	72	90	74	77	80
Lower heating value, kJ/kg	ASTM D224	42000	39500	41850	41000	40750
Cetane number	ASTM D613	49	45	48	47	46
Iodine value	ASTM D689	1.9	20.5	–	–	–
Carbon, %	–	86.5	83	–	–	–
Hydrogen, %	–	14.5	6.3	–	–	–
Nitrogen, %	–	–	0.5	–	–	–
Sulfur, %	–	–	1.2	–	–	–
Oxygen, %	–	–	6.5	–	–	–
Ash, %	–	–	2.5	–	–	–

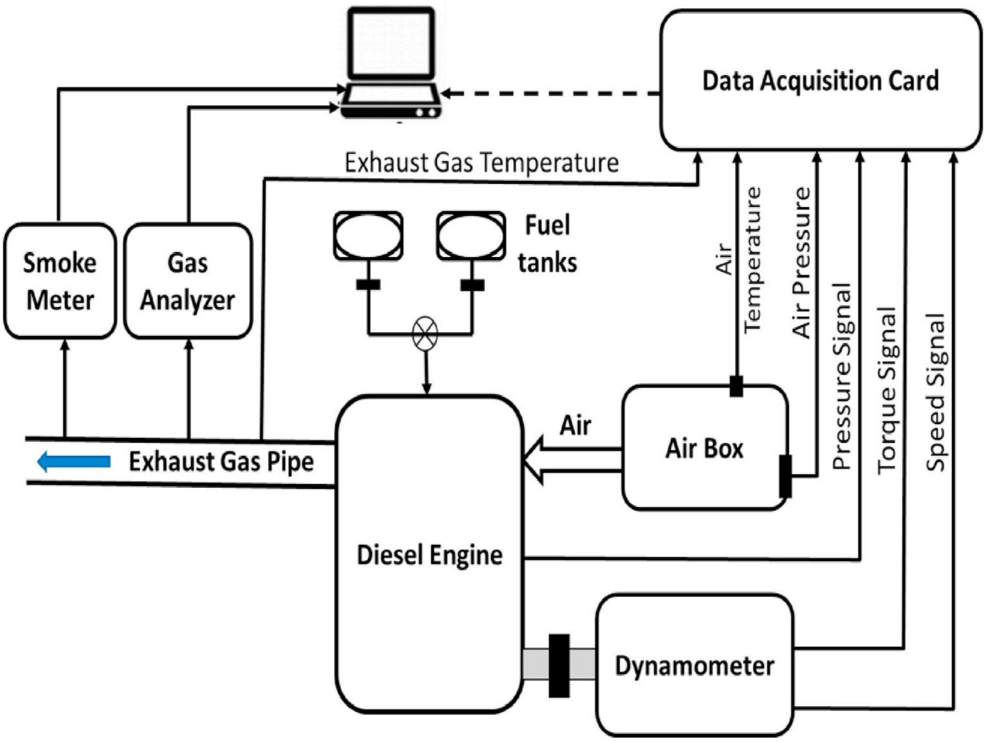


Fig. 6. Schematic diagram of the engine test rig.

Table 4
The test engine technical specifications.

Engine parameters	Specifications
Type	DEUTZ F1L511
Number of cylinders	1
Number of Cycles	Four-stroke
Cooling type	Air-cooled
Bore, mm	100
Stroke, mm	105
Compression ratio	17.5:1
Fuel injection advance angle	24° BTDC
Rated brake power, kW	5.775 at 1500 rpm
Number of nozzle holes	1
Injector opening pressure, bar	210

and the engine is loaded from 1 to 4 kW with intervals of 1 kW. Accordingly, the achieved results from the present paper are comprehensively discussed in the following subsections.

3.1. *Specific fuel consumption (BSFC)*

Brake specific fuel consumption is a very strong parameter in discussing the engine performance according to the varying test fuels. It refers to the consumed fuel amount which should be sprayed to reach a certain engine load [48,49]. Accordingly, the BSFC values for each test fuel are calculated using Equations (1) and (2).

$$Pe = \frac{2\pi.\omega.T}{1000} \tag{1}$$

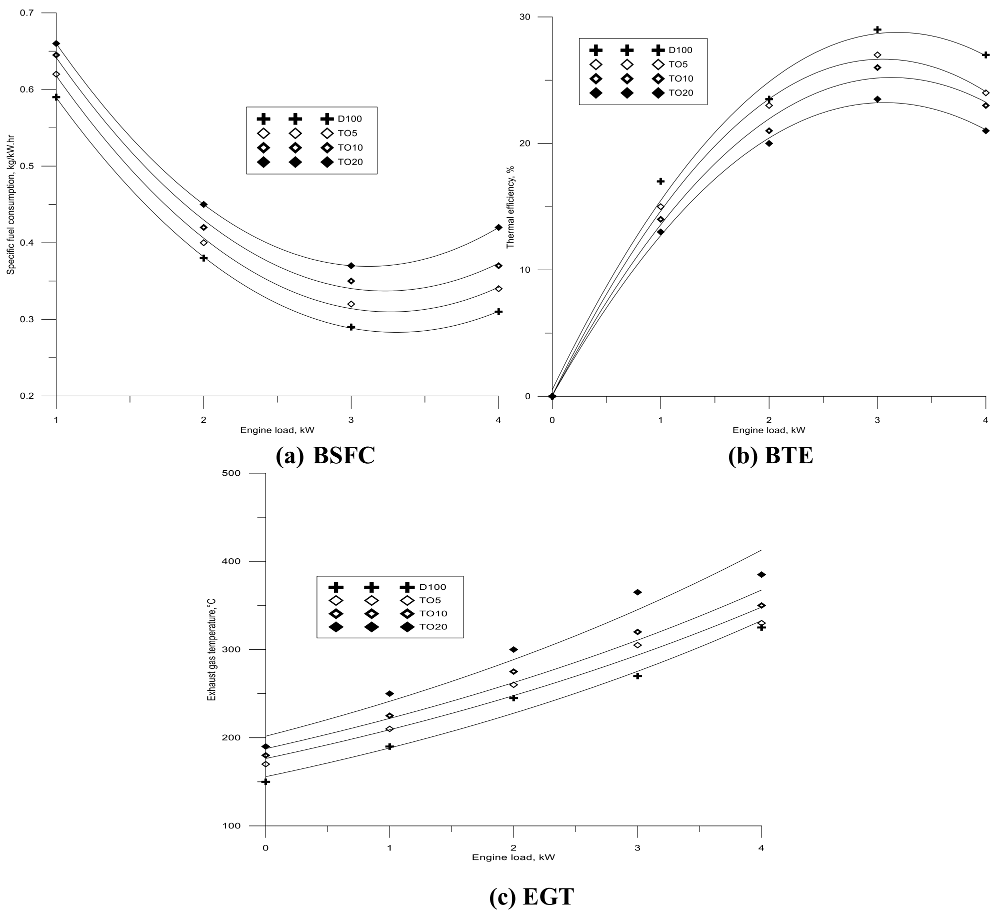


Fig. 7. Effect of tire oil blends on specific fuel consumption, thermal efficiency, and exhaust gas temperature.

$$BSFC = \frac{\dot{m}_f . 10^6}{P_e} \tag{2}$$

Where Pe, ω, and T are the brake power (kW), angular velocity (s-1), and torque (Nm) values used in the study, and $\dot{m}_f$ refers to the fuel flow rate (g·s-1).

BSFC values of diesel (D100) and tire oil-diesel fuel blends for TO5, TO10, and TO20 test fuels at different engine loads are illustrated in Fig. 7 (a). As shown from Table 3, tire oil has a lower calorific value and higher viscosity value, which results in the higher BSFC values of oil and diesel mixtures. The fuel consumption increases of tire oil blends were approximately proportional to the oil percentage, as shown in Fig. 7 (a). The reason behind the increment in BSFC with the addition of tire oil can be explained that the higher viscosities of binary oil blends produced the lower fuel penetration, injected fuel higher droplet size, combustion efficiency decrease, and improper fuel-air mixing. The lower output power of pyrolysis oil blends is due to the higher density compared to pure diesel. The engine used more fuel for tire oil blends than diesel oil to achieve the same power output. It can be seen from the figure that the BSFC value decreases until 4 kW as the engine load increases. This improvement in BSFC value for all test fuels, possibly with increased engine load, can be explained by the higher fuel burned at higher loads. When the engine load is set to a higher value, more fuel will be burned at higher loads with the increased amount of fuel sprayed from the injector. In this case, the temperature in the combustion chamber is expected to increase at high loads. In this case, the fuel will now enter a more suitable environment to ignite and combust more efficiently [50,51]. Consequently, it is seen that the BSFC value increase as the load increases. Similar BSFC changes have been reported by many researchers [52,53].

On the other hand, as seen in Fig. 7(a), when the engine load increased from 3 to 4 kW, the BSFC trend reversed, and BSFC values increased for all test fuels. This means that at a 4 kW engine load, so much fuel is injected that both the air/fuel ratio deteriorates and the hydrocarbon fuels can be removed from the exhaust tailpipe before they can be completely burned during the combustion cycles. This case caused the BSFC value to return to an increasing trend at 4 kW engine load. Similar results have been reported by previous researchers [54–57]. The average BSFC of TO5, TO10, TO20 and D100 were 0.365, 0.35, 0.415 and 0.315 kg/kW.hr, respectively at 100% of engine load. These findings were confirmed by Refs. [32,58–60].

3.2. *Brake thermal efficiency (BTE)*

Another performance benchmark handled in the present paper for a better comparison is the brake thermal efficiency (BTE). This is a significant performance indicator that gives an idea to the researchers that how chemical energy in the modified fuels could be converted into mechanical work. Therefore, high BTE values are desired for any modified test fuel for the fuel-researchers [59,52,61,62]. Accordingly, BTE is calculated using Equation (3).

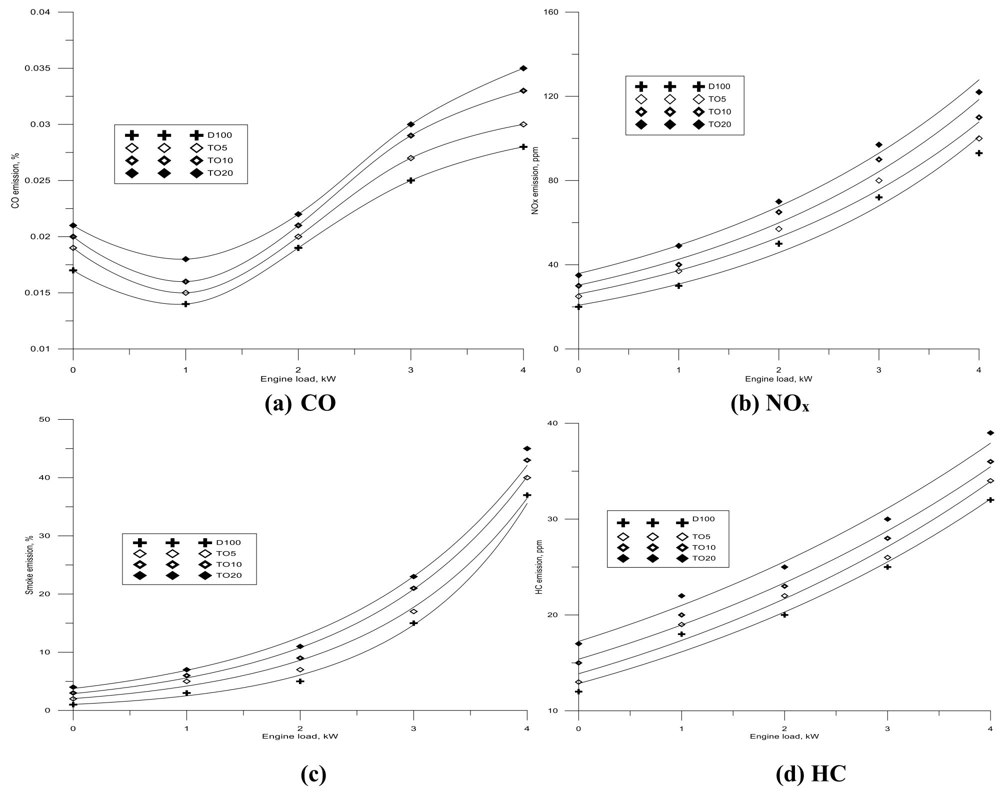


Fig. 8. Influence of oil blends on CO, NO_x, smoke, and HC emissions.

$$BTE = \frac{3600}{BSFC.LHV}.100 \quad (3)$$

In this equation, LHV refers to the lower heating value of test fuels, and its unit is MJ/kg. The impact of TO blends on the thermal efficiency of diesel engines was shown in Fig. 7 (b). Oil blends produced slightly lower thermal efficiencies about diesel fuel at all load range due to the lower calorific value, poor combustion characteristics, and lower volatility. The fuel atomization and evaporation are affected by the tire oil's higher viscosity and larger droplet size. The thermal efficiency was decreased as the oil percentage increased. As it can be understood from Equations (2) and (3), the BTE and BSFC have an opposite trend. TO blends achieved a lower injected fuel penetration than gas oil. The fuel-air mixing and spray cone angle are affected by the viscosity of the fuel. The narrow spray cone angle about gas oil caused pyrolysis oil blends' higher density and viscosity. Hence, BTE decreases percentages of oil blends TO5, TO10, TO20 about diesel fuel are 13, 18, and 21%, respectively, at full load. The results were confirmed with the literature [32,48,59,60].

3.3. Exhaust gas temperature (EGT)

Effect of TO mixtures with diesel fuel on exhaust gas temperature at engine load variation was described in Fig. 7(c). Because of the fuel consumption increase, the engine load increase is associated with the rise of EGT for all fuels. Exhaust gas temperatures of tire oil mixtures were higher due to improper combustion. Higher viscosities of oil blends resulted in lower fuel penetration and combustion efficiency decrease. The improper atomization of fuel spray was shown due to the oil's higher viscosity about gas oil. Higher pyrolysis oil volume percentages in oil blends resulted in the heat loss increase and decrease of thermal efficiency of diesel oil. As is seen in Fig. 7. (c), the EGT values gradually increase as the engine load increases. The increased fuel consumption can explain the reason behind it in high engine loads. Accordingly, the highest EGT value for each test fuel is noticed when the engine operates in 4 kW. The increases of EGT of oil mixtures TO5, TO10, and TO20 are 4.5, 13, and 22% at full load, respectively, related to diesel oil. These results were confirmed with references [33–36].

3.4. CO emission

Carbon monoxide is an incomplete combustion product, and therefore it presents an idea about the combustion phenomena for test fuels. CO emission is affected by many factors such as density, viscosity, the chemical structure of test fuels, air-fuel ratio, combustion duration, injection duration, nozzle hole diameter, etc. [63–66]. The engine brake power increased at lower engine loads associated with the decrease in CO emissions and then increased at the higher loads, as shown in Fig. 8 (a). The higher CO emissions of oil mixtures about diesel fuel were caused by the lack of oxygen, improper fuel-air mixture, and poor air entrainment [67,68]. The tire oil's higher viscosity and density led to more injected fuel, poor atomization, less volatility, rich combustion, and higher CO emissions. CO emissions of TO were increased than gas oil by the increase of oil blend ratio. The improper fuel atomization and less combustion efficiency of crude diesel resulted in higher CO emissions. Increases in CO emissions of TO5, TO10, and TO20 are 7, 19, and 35%, respectively, at 100% of engine load. The findings were confirmed with references [33,59,48].

3.5. NO_x emission

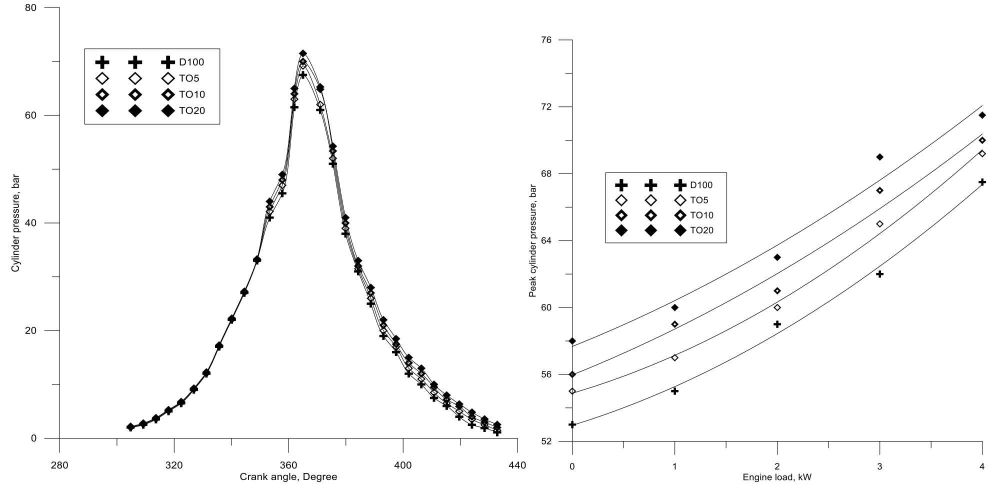
NOx emissions at engine load variation for oil mixtures were shown in Fig. 8 (b). The burned fuel, reaction time, and the in-cylinder temperatures are responsible for thermal NOx formation [62,69–71]. Tire oil has higher oxygen content, cylinder combustion temperatures than diesel fuel. NO_X formations were increased with the oil content increase. Higher cylinder temperature resulted in the highest NOx values for oil blends than pure diesel because tire oil has a lower ignition delay and higher cetane number. The higher thermal NOx was due to the less time spent in the fuel preparation, mixing with air, and the oxygen content. The less time of fuel mixing, preparation, and combustion produces the higher NO_x emission. The increased percentages in NO_x emissions for TO5, TO10, and TO20 are 7.5, 18, and 31%, respectively, at full load. The results were confirmed with the literature [34–39,49].

3.6. Smoke emission

Tire oil has higher molecular weight and viscosity than diesel fuel and leads to poor atomization, fuel-air mixing, and higher smoke emissions, as shown in Fig. 8 (c). Tire oil has higher aromatic content than diesel oil. The reduced catalytic activity of tire oil compared to crude diesel is due to the effect of sulfur content. Tire oil blends produced higher smoke emissions from diesel due to lower oxygen concentration and higher viscosity. The larger size of fuel particles and lower combustion efficiency was because of the tire oil's lower viscosity. Low fuel penetration led to the higher smoke emissions of TO compared to diesel oil. The increases in smoke emissions for TO5, TO10, and TO20 are 9, 15, and 20%, respectively, at 100% of engine load. The findings were confirmed with references [33–40, 72].

3.7. HC emissions

Variations of HC emissions for tire oil blends with the engine load were illustrated in Fig. 8 (d). A higher amount of injected fuel about diesel oil resulted in increased hydrocarbon concentration with engine load. Higher HC emissions of TO blends were due to unsaturated hydrocarbons, crevice volumes, and incomplete combustion. Higher density and viscosity led to higher HC emissions of tire oil blends in comparison to diesel oil. The short penetration of the fuel spray directed to the formation of unsaturated hydrocarbons in tire oil. The higher HC emissions of oil blends than pure diesel were due to the longer combustion of heavy oil molecules. The negative impact of higher viscosity of pyrolysis oil blends led to larger fuel droplet size and lower penetration. The combustion efficiency decreased, and improper fuel-air mixing produced higher HC emissions from crude diesel. The oil's higher viscosity led to vaporization problems, lower spray penetration, and higher HC concentrations. The HC emissions increase of TO5, TO10, and TO20



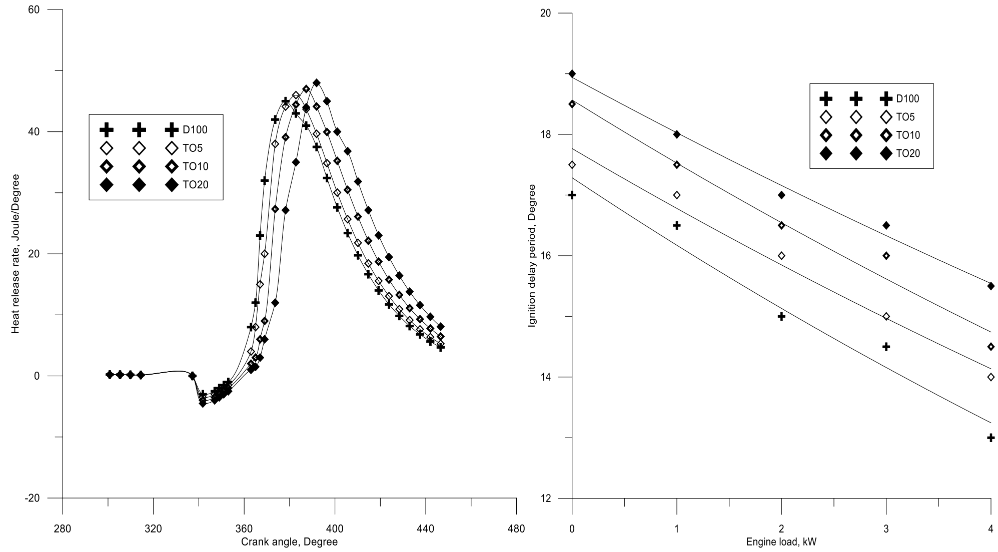
(a) Cylinder pressure **(b) Cylinder pressure versus engine load**

Fig. 9. (a) Cylinder pressure of oil blends with a crank angle at full load and (b) peak cylinder pressure at different loads.

are 7, 16, and 25%, respectively, at full load. The results were agreed with the literature [58,59].

3.8. Combustion characteristics

The cylinder pressures of tire oil mixtures at full load were described in Fig. 9 (a). In-cylinder pressure showed the same pattern for all fuels. As the engine load increased, the cylinder pressure increased as well. As compared to diesel fuel, oil blends had higher peak cylinder pressures. The increase in-cylinder pressures of oil mixtures are associated with the increase of oil percentage. Longer ignition delay and less oxygen content of tire oil affected the fuel droplets' evaporation process. Peak cylinder pressure measurements of oil blends are shown in Fig. 9 (b). The peak cylinder pressure is affected by the amount of fuel burned in premixed combustion. The mixture preparation and ignition delay influenced the premixed combustion. The Peak cylinder pressure of tire oil mixtures was higher than diesel fuel because of the aromatic content, which affected the premixed combustion phase. Another reason can be attributable to the cetane number of test fuels. As shown in Table 3, the tire oil has a lower cetane number than that of conventional diesel fuel. As it is well known, the ignition duration of test fuel gets longer as the cetane number increases. Therefore, the longest ignition delay is observed for tire oil blended test fuels, and this period brings longer as the concentration of tire oil in test fuel increases. As the ignition



(a) Heat release rate **(b) Ignition delay**

Fig. 10. Effect of tire oil blends on (a) HRR at different crank angles and (b) ignition delay at different loads.

delay duration extends for tire oil blended test fuels, the amount of fuel injected into the combustion chamber highly increases and accumulates therein. Then, reaching the appropriate temperature and pressure, this more fuel starts to ignite suddenly.

As a consequence of this sudden burning, the peak point is higher in these test fuels than conventional diesel fuel. Furthermore, the peak in-cylinder pressure points of waste blended oil test fuels gradually increase as the concentration of tire oil in test fuel increases due to the increasing cetane number of test fuels [58,59]. Peak cylinder pressures of diesel and tire oil blend TO5, TO10, and TO20 were 67.5, 69.2, 70, and 71.5 bar, respectively. The values of results agreed with research papers [32,41,45,47].

The heat release rate (HRR) of tire oil and their mixtures with diesel fuel at full load and rated speed was shown in Fig. 10 (a). All fuels showed a similar pattern. Maximum HRR values of oil mixtures were increased about diesel fuel. Peak heat release recordings were raised with the increase in oil percentage compared to pure diesel. The rise of cylinder pressures of oil blends about diesel oil led to the heat release rate increases. Higher aromatic content and longer ignition delay in tire oil produced higher heat release rates than diesel. The peak heat release rates of diesel, TO5, TO10, and TO20 are 44.5, 46, 47.5, and 48 J/Degree, respectively.

The results were confirmed with references [45,47,58]. Fig. 10 (b) indicated the ignition delay values of the test fuels from zero to 100% of engine load. A longer ignition delay was shown for tire oil blends than diesel fuel due to the lower cetane number. Ignition delay increased for all blends with the engine load increase. Probably, the reason behind the shorter ignition delay period for each test fuel in high engine load can be attributable to the high in-cylinder temperature in the elevated engine loads [58,59,68]. The increase in the ignition delay period of TO blends is associated with the oil percentage increase. Combustion duration increased for tire oil blends because of the higher fuel injected. Tire oil has a longer ignition delay than diesel oil because of the lower cetane number. The combustion duration is lower for oil blends are higher about diesel fuel because of the larger ignition delay and lower cetane number about diesel. CA50 defines the premixed combustion phase and the diffusion combustion start. The change from CA10 to CA90 shows the combustion duration. The air-fuel mixing, fuel droplet breakup, spray penetration, and vaporization affected the physical and chemical delay. The ignition delay increase of TO5, TO10, and TO20 is 4, 15, and 19%, respectively, at 100% engine load. The findings were confirmed with references [39,58].

4. Conclusion

The present study introduced the design and manufacturing of a waste tire pyrolysis production oil system. Tire oil was mixed with diesel oil in 5, 10, and 20% by volume percentages as TO5, TO10, and TO20. GC-MS, FTIR, and elemental analyses of tire pyrolysis oil were evaluated. The evaluated properties of tire oil blends agreed with ASTM standards in comparison to diesel oil. Performance, exhaust emissions, and combustion characteristics were assessed compared to crude diesel. The following conclusions can be described as:

- CFD analysis gave us the optimal reactor design, which offered the minimum thermal and mechanical stresses. The deformations in one side are 0.71375, 1.91675, 2.71685, and 3.17 mm at 200, 500, 700, and 1000 °C.
- O-Cymene and Benzene, 1, 2, 3, 4-tetramethyl were the main constituents in tire pyrolysis oil. The amines, alkenes, alkanes, phenyl rings, and aldehydes are shown in the FTIR analysis. The density of tire oil was higher than diesel oil. Viscosity, cetane number, and flash point of tire oil blends are higher than diesel fuel. The calorific value of tire oil was lower than pure diesel.
- Tire oil mixtures TO5, TO10, and TO20 showed increases in BSFC but achieved decreases in BTE and EGT related to diesel oil. The maximum reduction in thermal efficiency of TO20 was 21% of diesel oil.
- Tire oil blends TO5, TO10 and TO20 achieved increases in CO, HC, and smoke emissions related to diesel and showed decreases in NO_x emissions compared to diesel. The maximum increases in CO, smoke, and HC emissions of TO20 were 35, 20, and 25% of diesel fuel, respectively. The highest decline in NO_x concentration of TO20 was 19% of diesel oil.
- The peak cylinder pressures of tire oil blends were higher than diesel oil. Diesel and tire oil blends of TO5, TO10, and TO20 showed the peak cylinder pressures of 67.5, 69.2, 70, and 71.5 bar, respectively. Maximum HRR values of oil blends were lower than diesel fuel. The oil ratio increase led to the maximum heat release increase compared to pure diesel. The peak heat release rates of diesel, TO5, TO10, and TO20 are 44.5 kJ/Degree, 46 kJ/Degree, 47.5 kJ/Degree, and 48 kJ/Degree, respectively.
- The ignition delay period of oil mixtures decreased with the oil percentage increase in blends. The ignition delay values of D100, TO5, TO10, and TO20 at full load were 11, 12, 13, and 15 Degrees, respectively.
- Tire oil blends up to 20% volume percentages in oil blends can be used as alternative fuels as its properties are near to diesel oil, but there are increases in emissions and worst performance at higher percentages.

To sum up, based on the achieved results from the present study, the authors suggest that future works can evaluate these waste tire products as an energy source for internal combustion engines. Therefore, they can find a solution to rapidly depleting fossil fuel reserves and removing waste products from nature. Additionally, future works can focus on pulling back the worsened engine performance and exhaust emission characteristics by using some additives. In this way, the burning of these products will be more attractive in the future in terms of engine performance, combustion, and emission characteristics.

Credit author statement

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Declaration of competing interest

All authors have no conflict of interst.

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