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Article

Experimental study of combustion and performance efficiency of diesel engine fuelled with various blends of waste plastic oil

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Abstract: To find the alternatives to the non renewable energy sources are futures demand and disposal of plastic waste is today's need. Recovery of fuel oil from waste plastic gives the best option on both problems facing all over the world. The present experimental study deals with to analyze the performance and combustion parameters of oil synthesized by catalytic pyrolysis of waste polyethene; as it can be an alternative to diesel which is non renewable energy resource. Commercial diesel blend with condensed plastic oil as well as with residual plastic oil in the ratio of 10% (diesel 90% and plastic oil 10%), 20% (diesel 80% and plastic oil 20), 30% (diesel 70% and plastic oil 30%) and 50% (diesel 50% and plastic oil 50%) in volume. Combustion analysis and performance studies was carried out at 25%, 50%, 75% and 100% load condition in internal combustion engine set up under test is Kirloskar TV1 to understand the feasibility of utilizing plastic oil as substitute fuel to commercial diesel. This study proved that 50% blending gives satisfactory results for performance and combustion parameters than 100% use of commercial diesel.

Keywords: pyrolysis; polyethylene; combustion; performance; internal combustion engine

1. Introduction

From the previous two decades, there is a progressive awareness on the fuel substitute use in vehicles because of the effect of the transportation sector on conservatory gases and inadequate petroleum sources. Fuel derived from bio waste that are methanol, ethanol have been shown good results as alternative fuels for vehicles because of their physical state, physical properties which are nearly similar to that of commercial diesel fuel [1–5].

Due to higher oxygen content and octane number of alcohols, its combustion in gasoline engines seems excellent results than the pure gasoline whereas it shows a few difficulties in diesel engine due to its high latent heat of vaporization, low cetane number. Methods like alcohol fumigation, diesel-alcohol blend, alcohol-diesel fuel emulsion are used to come out form this problem [6,7]. Blends like alcohol, biodiesel; fuel derived from plastic waste is also a hopeful alternative as fuel in internal combustion engine [8]. Plastic made from petroleum. It refers to their malleability or plasticity during manufacture, which allows them to be cast, pressed, or extruded into a variety of shapes such as films, fibers, plates, tubes, bottles, boxes, and much more [9], cause to generates tones of plastic waste every day. Considering this fact, many authors [8,10,11] had worked on oil extraction from plastics as an alternative source of fuels for the diesel engines, to save environment and accumulation of plastic waste. Here we are studying the feasibility of use of derived plastic oil in internal combustion diesel engine by analyzing its performance and combustion parameters over various blends (10%, 20%, 30%, 40%, 50%) at various loads (25%, 50%, 75%, 100%).

2. Material and method for synthesis of liquid fuel by pyrolysis of plastic waste

2.1. Materials

The raw material used for the process is polyethylene samples collected from tea corners, canteen, small hotels, and general stores. The collected plastic is associated with some foreign materials as the material contains milk bags, oil bags, carry bags, food storage bags. All material was air dried without washing and used as it is for further procedure.

2.2. Experimental

Cracking of polyethylene was carried out in reactor placed on gas stove with temperature and pressure controlled measurement systems. At atmospheric pressure polymer cracking was carried out in a batch reactor (500 g feed) with 20% catalyst. Heating temperature was found 24 ℃ to 306 ℃ maximum. The polyethylene melted and converts into vapors containing different polymeric chains with different carbon number. The fumes are condensed in a coiled condenser by using tab water as a cooling medium. The carbon chains from C-7 to C-21 get liquefied and collected in a receiver-1. The uncondensed fumes that are from C-1 to C-4 are passes into polymer gas storage bag through receiver-2 and reciver-3, in which receiver-3 containing water and receiver-2 kept empty to prevent mixing of water and liquid fuel in receiver-1 due to back pressure. While the residual oil left in reactor can be collected through lower outlet-14. The reaction was completed within 3 h and produces 88% plastic liquid fuel, 12% gaseous fuel only 1% residue was left over associated with 20% catalyst (as shown in **Figure 1** and **Table 1**).

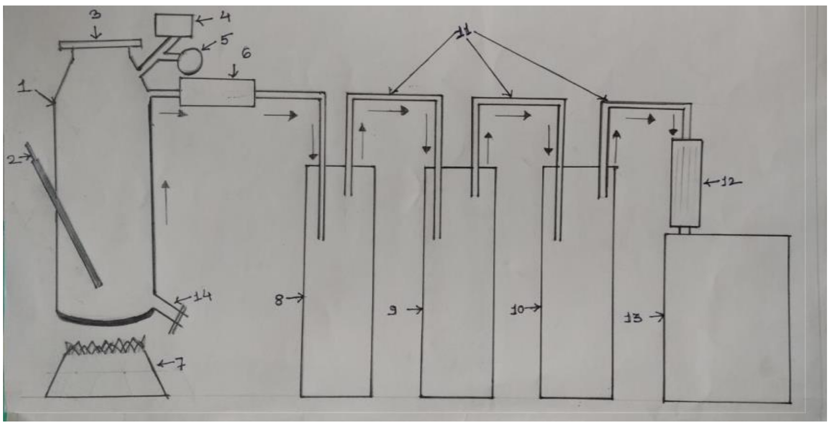

Figure 1. Experimental setup for pyrolysis of plastic waste.

Table 1. Physical properties of condensed and residual oil obtained.

Properties	**Value (Condensed oil)**	**Value (Residual oil)**
Solubility	Chloroform	Chloroform
Boiling point (Initial) (degree celcious)	60 °C	40 °C
Refractive Index	1.4294	1.4500
Density (g/cm^3)	0.774	0.788
Specific gravity (g/cm^3)	0.7762	0.790
Surface Tension (dyne per centimeter)	47.9059	49.01

3. Experimental setup to study of combustion and performance efficiency of diesel engine fuelled with various blends of waste plastic oil

The performance, combustion parameters of obtained condensed and residual oil during catalytic pyrolysis of polyethene can be analyzed by using diesel engine set up under test is Kirloskar TV1 (as shown in **Figure 2**).

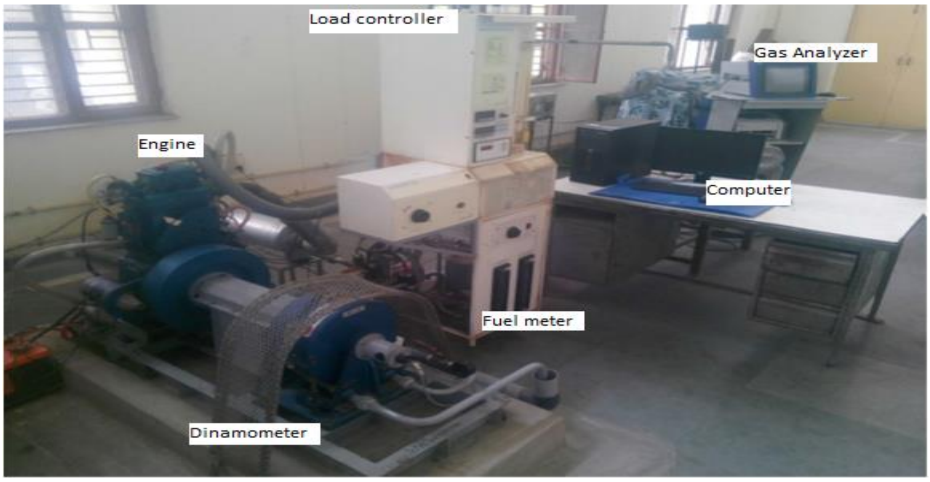

Figure 2. Experimental setup to study of combustion and performance efficiency of diesel engine.

Engine details:

Internal combustion engine set up under test is Kirloskar TV1 having power 5.20 kilo Watt at 1500 revolution per minuets which is 1 cylinder, four stroke, constant speed, water cooled, diesel engine, with cylinder bore 87.50 mm, stroke length 110.00 (mm), connecting rod length 234.00 mm, compression ratio 17.50, swept volume 661.45 (cubic centimeter) (as shown in **Table 2**).

Table 2. Performance parameters.

Orifice diameter (mm)	20.00
Orifice coefficient of discharge	0.60
Dynamometer arm length (mm)	185
Fuel Pipe diameter (mm)	12.40

Table 2. (*Continued*).

Ambient temperature (degree Celsius)	27
Pulses per revolution	360
Fuel type	Diesel and various blends of condensedand residual oil obtained with diesel
Fuel density (kilogram per cubic meter)	
Diesel	0.81260
10% condensed oil	0.80321
20% condensed oil	0.8020
30% condensed oil	0.7978
50% condensed oil	0.7940
10% residual oil	0.8192
20% residual oil	0.8181
30% residual oil	0.8166
50% residual oil	0.8145
Calorific value of fuel kilo joule per kilogram	
Diesel	43,000
10% condensed oil	42,000
20% condensed oil	41,500
30% condensed oil	41,000
50% condensed oil	40,000
10% residual oil	41,800
20% residual oil	41,100
30% residual oil	40,400
50% residual oil	39,000

4. Performance analysis

4.1. Mechanical efficiency (%)

Mechanical efficiency is defined as the ratio of brake power to the indicated power or the ratio of brake thermal efficiency to the indicated thermal efficiency. **Figure 3** and **Table 3** indicates that it increases with increasing load and it is almost equivalent to pure diesel at all loads for all blends.

Table 3. Mechanical efficiency of condensed and residual oil at all loads.

Load (%)	**Condensed oil**				**Residual oil**				**Diesel**
	10%	**20%**	**30%**	**50%**	**10%**	**20%**	**30%**	**50%**	
25	25.72	27.17	25.7	26.44	24.98	27.41	26.51	27.76	25.1
50	39.04	41.43	38.92	40.49	39.7	40.81	41.13	40.49	39.6
75	49.88	50.93	50.04	49.27	51.29	50.67	49.73	49.8	50.3
100	57.68	58.22	58.67	57.95	57.9	57.95	57.98	57.62	58.2

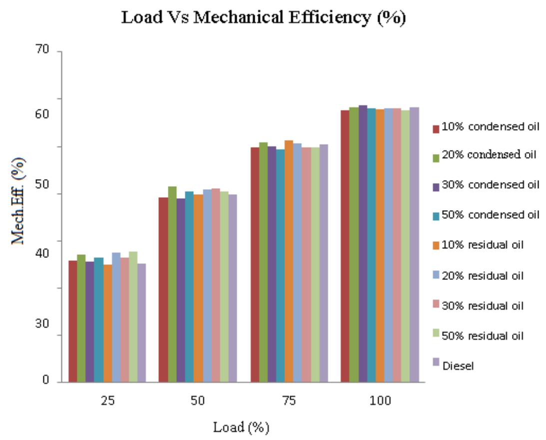

Figure 3. Mechanical efficiency of condensed and residual oil at all loads.

Figure 3 shows variation in mechanical efficiency with load. From the figure it is observed that mechanical efficiency of all blends is higher than that of pure diesel at 25% load. But at full load only 10% and 30% condensed oil has higher mechanical efficiency. This may be due to the more oxygen content of polyethylene fuel blends which leads to complete combustion which will increase the brake power and hence the mechanical efficiency.

4.2. Mean effective pressure (MEP)

Mean effective pressure is that of the average pressure inside the cylinders of an indoor combustion engine supported the calculated or measured power output. It increases as manifold pressure increases. For any particular engine, operating at a given speed and power output, there will be indicated mean effective pressure and a corresponding brake mean effective pressure derived from indicated power and brake power respectively (as shown in **Table 4**).

Table 4. Indicated mean effective pressure at all loads.

Load(%)	Condensed oil				Residual oil				Diesel
	10%	20%	30%	50%	10%	20%	30%	50%	
25	4.57	4.42	4.37	4.37	4.46	4.29	4.33	4.33	4.4
50	5.44	5.09	5.3	5.26	5.43	5.5	5.45	5.36	5.4
75	6.29	6.09	6.08	6.4	6.21	6.32	6.29	6.26	6.3
100	7.16	7.18	7.31	7.22	7.27	7.36	7.38	7.36	7.2

The **Figure 4** shows that indicated and brake mean effective pressure increases steadily with increasing load. 10%, 50% condensed and 30%, 50% residual oil shows higher mean effective pressure than that of pure diesel.

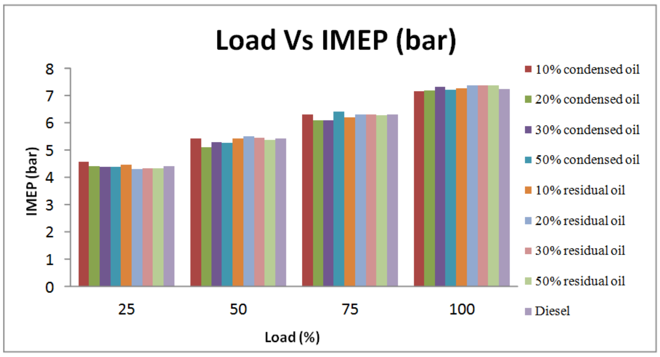

Figure 4. Indicated mean effective pressure at all loads.

4.3. Brake mean effective pressure (BMEP)

Mean effective pressure is that the average pressure inside the cylinders of an indoor combustion engine supported the calculated or measured power output. It increases as manifold pressure increases. For any particular engine, operating at a given speed and power output, there will be indicated mean effective pressure and a corresponding brake mean effective pressure derived from indicated power and break power respectively (as shown in **Table 5**).

Table 5. Brake mean effective pressure (BMEP) at all loads.

Load (%)	Condensed oil				Residual oil				Diesel
	10%	20%	30%	50%	10%	20%	30%	50%	
25	4.57	4.42	4.37	4.37	4.46	4.29	4.33	4.33	4.42
50	5.44	5.09	5.3	5.26	5.43	5.5	5.45	5.36	5.43
75	6.29	6.09	6.08	6.4	6.21	6.32	6.29	6.26	6.3
100	7.16	7.18	7.31	7.22	7.27	7.36	7.38	7.36	7.24

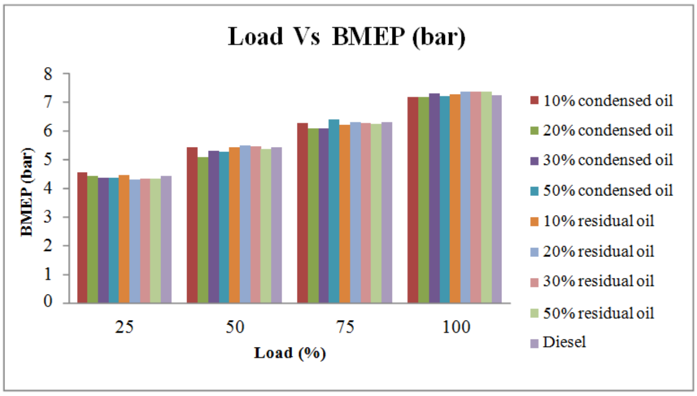

Figure 5. Brake mean effective pressure (BMEP) at all loads.

The **Figure 5** shows that indicated and brake mean effective pressure increases steadily with increasing load. 30% condensed and all blends of residual oil shows higher mean effective pressure than that of pure diesel at full load.

4.4. Torque (Nm)

Torque is the force required to change the axis, a force that tends to cause the rotation. The **Figure 6** indicates that it increases gradually along with increasing load and most often similar as that of pure diesel for all blends at all load except 30% condensed oil and 20% residual oil shows higher torque than that of pure diesel at full load (as shown in **Table 6**).

Table 6. Torque for condensed and residual oil at all loads.

Load (%)	Condensed oil				Residual oil				Diesel
	10%	**20%**	**30%**	**50%**	**10%**	**20%**	**30%**	**50%**	
25	6.19	6.32	5.91	6.08	5.87	6.19	6.04	6.32	5.86
50	11.17	11.1	10.85	11.21	11.35	11.81	11.8	11.42	11.34
75	16.5	16.33	16	16.59	16.75	16.87	16.46	16.4	16.67
100	21.74	22.01	22.58	22.02	22.75	22.45	22.52	22.32	22.19

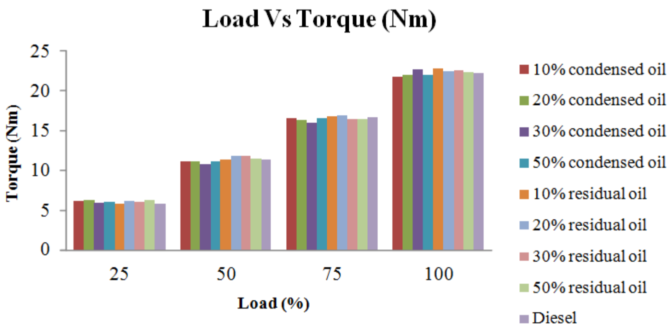

Figure 6. Torque for condensed and residual oil at all loads.

4.5. Specific fuel consumption (kilogram per Kilowatt hour)

The fuel utilization property of an engine is usually referred in terms of specific fuel consumption in kilograms per kilowatt-hour. It is key parameter that represents how superior the engine performance is. It is decreases with increase in thermal efficiency of the engine. **Figure 7** and **Table 7** indicates that the specific fuel consumption decreases continuously for all blends as load increases. This is because, when the load increases, temperature inside the cylinder increases reduces delay period, total combustion timing increases and results in proper combustion of fuel. It can also be noticed that the trend of falling specific fuel consumption corresponding to load applied is almost the same for pure diesel and 50% condensed and 50% residual oil blend, however it differs for lesser ratio of blend and lower load.

These trends of specific fuel consumption are all because of possessing high calorific value of blends and better combustion.

Table 7. Specific fuel consumption for condensed and residual oil at all loads.

Load (%)	Condensed oil				Residual oil				Diesel
	10%	**20%**	**30%**	**50%**	**10%**	**20%**	**30%**	**50%**	
25	0.59	0.55	0.57	0.54	0.58	0.56	0.55	0.53	0.54
50	0.38	0.38	0.39	0.35	0.36	0.36	0.36	0.38	0.36
75	0.32	0.31	0.3	0.3	0.28	0.3	0.3	0.31	0.32
100	0.3	0.29	0.28	0.27	0.32	0.28	0.28	0.29	0.29

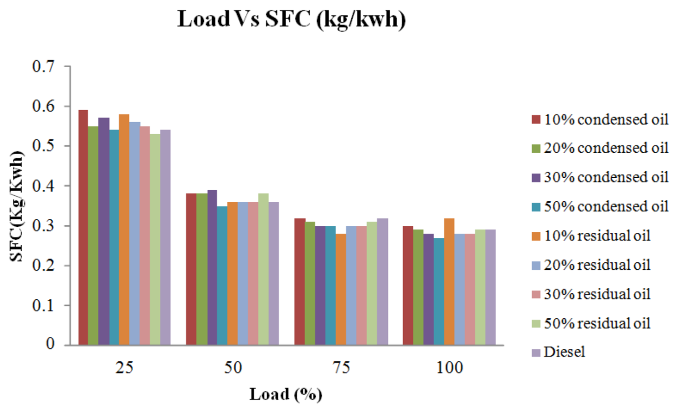

Figure 7. Specific fuel consumption for condensed and residual oil at all loads.

5. Combustion analysis

5.1. Variation of cylinder pressure with crank angle at full load

Figure 8 shows the variation of cylinder pressure with crank angle for diesel, blend of 10%, 20%, 30%, 50% condensed oil and residual oil with 90%, 80%, 70%, 50% diesel at 1500 rpm and full load condition. From this figure, it is clear that the peak cylinder pressure is increased with the increase of condensed oil concentration with blends. However, the combustion process of test fuels is similar, consisting of a phase of premixed combustion followed by the phase of diffusion combustion. It can be noted from the figure that peak cylinder pressure occurs after TDC at full load.

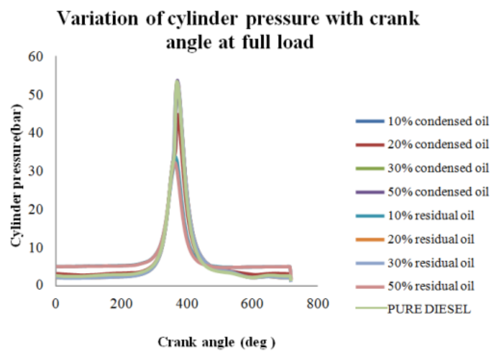

Figure 8. Variation of cylinder pressure with crank angle at full load.

This is due to a prolonged ignition delay period which extends the premixed combustion phase up to 10–120 after TDC. The maximum peak pressure for pure diesel, blend of 10%, 20%, 30%, 50% condensed oil and residual oil with 90%, 80%, 70% 50% diesel are 53.36 bar, 52.2 bar, 44.75 bar, 52.61 bar, 53.67 bar, 33.72 bar, 53.01 bar, 53.06 bar and 32.28 bar respectively.

5.2. Variation of mass fraction burned with crank angle

Figure 9 shows variation of mass fraction burnt for poly (ethylene) fuel blends and diesel with the crank angle at full load. At full load conditions mass fraction burnt for diesel is more than that of blends of 10%, 30%, 50% condensed oil and that of 20%, 30% residual oil. The reason probably may be due to longer ignition delay of diesel which leads to larger amounts of fuel accumulation in the combustion chamber at the time of premixed combustion stage, leading to higher mass burning rate.

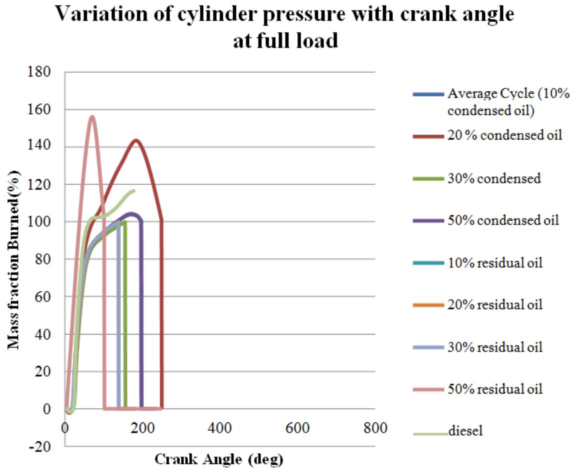

Figure 9. Variation of mass fraction burned with crank angle at full load.

Blends of 20% condensed and 10% and 50% residual oil show slightly higher mass fraction burnt to diesel. The highest rate of burning shows the competent rate of combustion.

5.3. Heat release rate (HRR)

Heat release rate is the rate at which the chemical energy of the fuel is released by the combustion process in a compression ignition engine. The heat release rate is used to identify the start of combustion, the fraction of fuel burned in premixed mode and differences in combustion rates of fuel. The direct injection diesel engine combustion process is divided into premixed phase and diffusion phase. **Figure 10** shows the variation of heat release rate with respect to crank angle at full load.

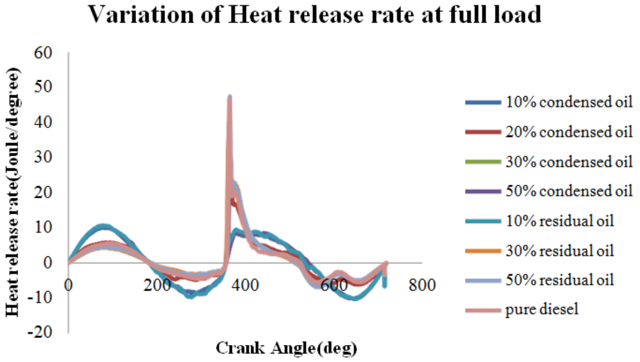

Figure 10. Heat release rate for condensed and residual oil at full load.

From the **Figure 10** maximum heat release rate is seen for pure diesel than blends of condensed and residual oil. This may be due to shorter delay and lower calorific value of poly (ethylene) fuel than pure diesel which leads to lower peak heat release rate. It is also observed that combustion starts earlier for blends. However, the heat release during diffusion combustion phase for blends is almost identical to diesel fuel. This is because of excess oxygen content of condensed and residual oil left over during the earlier combustion stage continuing to burn inthe later stage.

6. Conclusion

The performance and combustion characteristics of derived plastic oil from degradation of waste plastic are compared with the conventional diesel fuel. Results are summarized as follows:

- The mechanical efficiency of all blends is higher than that of pure diesel at 25% load. But at full load only 10% and 30% condensed oil has higher mechanical efficiency. This may be due to the more oxygen content of polyethylene fuel blends which leads to complete combustion which will increase the brake power and hence the mechanical efficiency.
- It also shows that indicated and brake mean effective pressure increases steadily with increasing load. 10%, 50% condensed and 30%, 50% residual oil shows higher mean effective pressure than that of pure diesel. It indicates that the blends of this plastic fuel have better ignition quality and higher energy content than that of pure diesel which results for complete combustion of fuel with high power output which causes high pressure during power stroke resulting in higher MEP.
- It can also be noticed that the trend of falling specific fuel consumption corresponding to load applied is almost the same for pure diesel and 50% condensed and 50% residual oil blend, however it shows smaller change for lesser ratio of blend at lower load.
- The trends of specific fuel consumption are all because of possessing high calorific value of blends and better combustion.
- The peak pressure takes place after TDC which ensures smooth and safe operation. Otherwise, peak pressure found very close or before TDC results in knocking.
- Maximum heat release rate is seen for 50% blend of residual oil than pure diesel. This may be due to the higher heating value of plastic fuel blends than diesel.
- At full load conditions mass fraction burnt for diesel is more than that of blends of 10%, 30%, 50% condensed oil and that of 20%, 30% residual oil. The reason probably may be due to longer ignition delay of diesel which leads to larger amounts of fuel accumulation in the combustion chamber at the time of premixed combustion stage, leading to higher mass burning rate. Blends of 20% condensed and 10% and 50% residual oil show slightly higher mass fraction burnt to diesel. The maximum rate of burning indicates the competent rate of combustion
- Overall, it’s a concludes that up to 10% to 30% condensed oil blends and 50% residual oil blend can be used for vehicles as an alternative source of diesel while 50% condensed and 10%–30% residual oil blends can be suitable as industrial fuel purpose in boilers and kilns, furnaces.

Author contributions: Conceptualization, BV and RP; methodology, BV and RP; software, BV and RP; validation, BV and RP; formal analysis, BV and RP; investigation, BV and RP; resources, BV and RP; data curation, BV and RP;

writing—original draft preparation, BV and RP; writing—review and editing, BV and RP; visualization, BV and RP; supervision, BV and RP; project administration, BV and RP; funding acquisition, BV and RP. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest: The authors declare no conflict of interest.

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