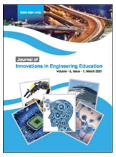

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Thermal balance sheet of plastic pyrolysis oil on a single cylinder DI engine

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Abstract

An internal combustion engine can be considered a thermodynamic open system. Investigation on blends of distilled plastic oil was performed on a constant speed diesel engine at various loading conditions. The thermal balance sheet was prepared concerning useful work i.e. heat equivalent to useful work, heat loss in jacket cooling water, heat loss in the exhaust gas, and unaccounted heat i.e. heat loss in radiation. Blends up to 20% by volume of various high-grade plastic fuels were used. The thermal balance sheet indicates that heat equivalent to brake power of 5PDB is higher than diesel at low load and 10PDB has higher HBP than diesel at high load. All blends of PDB indicate higher heat conversion into useful work. The exhaust gas temperature of all blends of high-grade plastic fuel is lower than that of diesel which shows a better conversion rate of produced heat in the cylinder into useful work.

Abbreviations and acronyms

5 PDB	: 5% Blend of High-grade plastic oil with 95% diesel
10 PDB	: 10% Blend of High-grade plastic oil with 90% diesel
15 PDB	: 15% Blend of High-grade plastic oil with 85% diesel
20 PDB	: 20% Blend of High-grade plastic oil with 80% diesel

1. Introduction

The increase in demand for natural petroleum resources has attracted the interest of many researchers to find a substitute for natural petroleum. Plastic being the byproduct of petroleum products, can be used to produce petroleum-grade oil. Plastic undergoes thermal degradation in absence of oxygen to produce oil. Thermal degradation in absence of oxygen is thermal pyrolysis. Thermal pyrolysis followed by bypassing the gas with a catalyst is called catalytic pyrolysis. Catalyst commonly used are zeolite, silica-alumina, FCC catalyst, alumina, etc. [1] . On thermal pyrolysis of plastic, petroleum grade fuel is obtained which has the same fuel property as that of the diesel [2]. The end product of thermal pyrolysis depends upon the type of plastic feed. The presence of polyethylene increases alkane content, polypropylene increases alkene content and polystyrene increases aromatic content [3]. The oil obtained from thermal pyrolysis contains both the shorter and longer hydrocarbon chain. Oil obtained from thermal pyrolysis goes through fractional distillation to reduce the carbon chain. The distilled oil has good fuel quality and high energy content [4]. Fuel property of blends of plastic oil with diesel up to 20% by volume has comparative fuel property character as that of EN 590 diesel fuel standard. [5]. The engine was able to run with 100% waste plastic oil [6]. The waste plastic pyrolysis oil is a suitable fuel for a diesel engine, without any modification made on the engine, and it has the property equivalent to diesel

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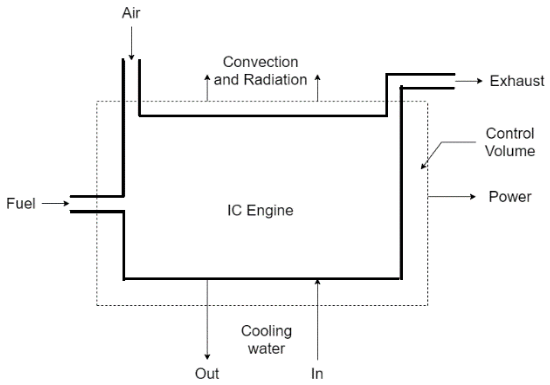

Figure 1: Energy flow of CI engine at control volume

A thermal balance sheet is a useful tool that provides information on the energy distribution of the fuel energy supplied and identifies the possible losses of an engine. The first law of thermodynamics is associated with thermal balance, energy, or heat balance while the second law is associated with irreversibility identification [8, 9]. The first law of thermodynamics is focused on energy conservation, it reflects on the energy losses from the engine. The second law of thermodynamics provides detailed insight into engine processes. It assigns magnitude to terms such as exhaust gas and heat losses. By doing so, it recognizes certain engine processes and parameters that can help to improve engine performance.

Various researches have been done on thermal balance sheets using various terms but the principle of overall research is the same i.e. first law of thermodynamics [10, 11]. The thermal balance sheet is linked with control volume. From Figure 1, it can be observed that a system is linked with space which is surrounded by an imaginary surface, normally called a control surface. It is easier to visualize the inflows and outflows of energy, in and out of the system through the heat balance sheet [12].

Table 1: Availability losses in naturally aspirated diesel [12]

Loss Mechanism	Loss, a fraction of fuel availability
Combustion	0.225
Exhaust	0.144
Heat transfer	0.135
Aerodynamic	0.047
Mechanical friction	0.048
Total Losses	0.599

Total losses that occurred in a naturally aspirated CI engine are illustrated in Figure 1. It is observed that combustion loss is dominant which is 22.5% while the exhaust and heat transfer losses are respectively 14.4% and 13.5%.

The outcome from the heat generated in the cylinder is brake power, heat loss in jacket cooling water, and heat loss in the exhaust. The undetermined heat loss is unaccounted heat or miscellaneous heat. The unaccounted heat is referred to as heat loss in radiation. In addition to these heat losses, lubricating oil heat loss (where cooling is done separately) is used by many researchers [11, 12]. So fluctuation is shown in much thermal balance sheet due to addition of lubricating oil heat loss. Exhaust heat loss is usually calculated by using an exhaust calorimeter [12]. 12% of the exhaust heat loss is radiated to the surrounding and the remainder here is transferred to the cooling medium. Around 50% of frictional power is dissipated among piston and piston rings and cylinder walls and later lost to cooling medium as heat [12].

The thermal balance sheet of conventional diesel shows 16% to 35% loss in cooling, 23% to 37% loss in the exhaust, and 2-6% for other loss; while the brake power of CI engine varies from 34% to 38% [13]. On replacing conventional diesel with blends of alternative fuel [14, 15, 16] with diesel or fumigated with alternative fuel [17], there shows considerable change in heat loss and engine performance.

Design factors, load, compression ratio, valve diameter, valve lift, flame speed, and engine speed are some of the major factors after the thermal energy balance of an IC engine. The effect of these variables on thermal balance varies from fuel to fuel and engine to engine [18].

It is noticeable that very small data is available on the thermal balance of diesel engines running on plastic pyrolysis oil. The objective of the study is to establish a thermal balance of a constant-speed diesel engine having an eddy current dynamometer while using blends of plastic oil as an alternative fuel.

2. Materials and methods

2.1. Fuel production

Crude plastic oil was produced in a one kg batch reactor through thermal pyrolysis at 450°C. Obtained crude oil was allowed to fractional distillation by following the standard ASTM D86-20b. Recovery was obtained at 200°C, 290°C, and till the final boiling point. The investigation is focused on oil recovered between the temperature ranges of 200°C to 290°C. The oil obtained at this temperature range is regarded as high-grade plas-

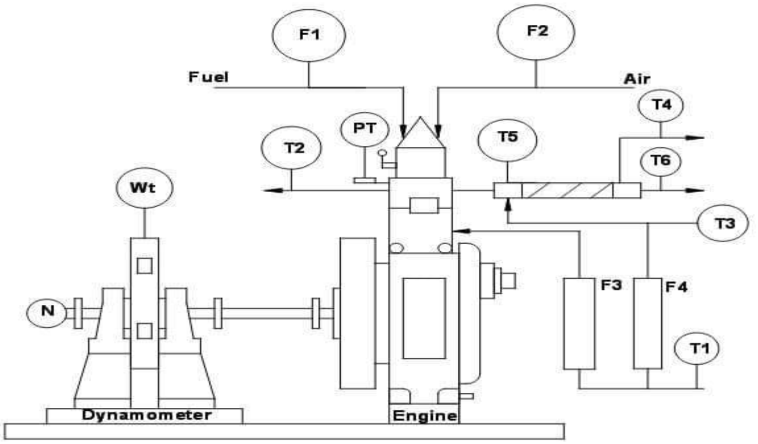

Figure 2: Schematic diagram of research engine

tic oil (PDB). Blends of PDB with diesel by volume up to 20% were tested.

2.2. Fuel property testing

Density was measured by a hydrometer method [19, 20]. Calorific value was measured by Digital Bomb Calorimeter – Model CC01/M2 and Viscosity was, measured by ASTM D445 [21].

2.3. Engine and instrumentation

IC engine set up under test is Research Diesel Engine having power 3.50 kW at 1500 rpm 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 18.00, Swept volume 661.45 (cc). Schematic diagram of diesel engine is shown in the Figure 2.

Combustion parameters

Air Density (kg/m^3) : 1.17

Polytrophic Index : 1.12

Adiabatic Index : 1.41

Number of Cycles : 10

Smoothing : 2

TDC Reference : 0

Cylinder Pressure Reference : 1

Performance parameters

Orifice Diameter (mm) : 20.00

Pulses Per revolution : 360

Dynamometer Arm Length (mm) : 185

Ambient Tempt. (°C) : 27

In Figure 2,

F1 : Fuel consumption (kg/hr)

F2 : Air consumption (kg/hr)

F3 : Jacket cooling water (kg/hr)

F4 : Calorimeter water flow (kg/hr)

T1 : Jacket water inlet temp (°C)

T2 : Jacket water outlet temp (°C)

T3 : Calorimeter water inlet temp (°C)

T4 : Calorimeter water outlet temp (°C)

T5 : Exhaust gas to calorimeter inlet temp (°C)

T6 : Exhaust gas from calorimeter outlet temp (°C)

2.4. Theory of engine balance

From the first law of thermodynamics, for a control volume, the steady flow equation will be [12, 22, 23].

$$Q_s = Q_{bp} + Q_{jw} + Q_{ex} + Q_{misc} \tag{1}$$

Where,

Q_s : Energy supplied by the fuel

Q_{bp} : Output work delivered in the form of brake power

Q_{jw} : Output work delivered in the form of heat to jacket cooling water

Q_{ex} : Output work delivered in the form of heat to exhaust

Q_{misc} : Output work delivered in the form of heat to miscellaneous loss

$$Q_s = M_f \times C_f \tag{2}$$

Where,

M_f : Fuel flow rate

C_f : Calorific Value of the fuel

$$\text{Brake Power (BP)} = \frac{2\pi NT}{60 \times 100}\ (\text{kW}) \tag{3}$$

Where,

N : revolution (rev/s)

T : Torque offered by the engine (N.m)

$$\text{HBP} = \text{BP} \times 360 \tag{4}$$

$$Q_{bp}(\%) = \frac{\text{HEqv} \times 100}{\text{HFuel}} \tag{5}$$

$$\text{HJW} = \text{F3} \times C_p\text{W} \times (\text{T2} - \text{T1}) \tag{6}$$

$$Q_{jw}(\%) = \frac{\text{HJW} \times 100}{\text{HFuel}} \tag{7}$$

$$C_{pex} = \frac{\text{F4} \times C_p\text{W} \times (\text{T4} - \text{T3})}{(\text{F1} + \text{F2}) \times (\text{T5} - \text{T6})} \tag{8}$$

Where,

C_{pex} = Specific heat of exhaust gas (kJ/kg°K)

C_{pw} = Specific heat of water (kJ/kg°K)

T_{amb} = Ambient Temperature (°C)

$$\text{HGas (KJ/h)} = (\text{F1} + \text{F2})\, C_{pex}\, (\text{T5} - T_{amb}) \tag{9}$$

$$\text{HGas (\%)} = \frac{\text{HGas} \times 100}{\text{HFuel}} \tag{10}$$

$$\text{HRad (\%)} = \text{HFuel (100\%)} - \{\text{HBP (\%)} + \text{HJW (\%)} + \text{HGas (\%)}\} \tag{11}$$

Where,

HRad : Heat to Radiation

HGas : Heat in Exhaust Gas

HFuel : Heat Supplied by Fuel

HJW : Heat in Jacket Cooling Water

HBP : Heat Equivalent to Brake Power

HEqv : Heat Equivalent to Useful Work

3. Result and discussion

Blends of high-grade plastic fuel have a higher calorific value than diesel. This is due to the presence of lighter hydrocarbon in plastic fuel. Higher calorific value leads to proper burning of the fuel sample. Fuel property of tested samples are listed in Table 2. From Table 2 it can be observed that the density and viscosity of 10PDB, 15PDB and 20PDB are below diesel.

Table 2: Fuel property

Fuel Property	10 PDB	15 PDB	20 PDB	Diesel
Calorific Value (MJ/Kg)	47.101	47.675	48.173	46.67
Density (kg/m^3)	826.4	824.8	823.4	828.5
Viscosity (cSt)	2.227	2.359	2.40	2.54

The thermal balance sheet of CI engine operating on diesel, blends of high-grade diesel fuel with diesel by volume was established at various loads. The thermal balance sheet shows the energy conversion into useful work i.e., heat equivalent to brake power (HBP), heat in jacket cooling water (HJW), heat loss through the exhaust (HGas), and other losses i.e., radiation and unaccounted for losses (HRad).

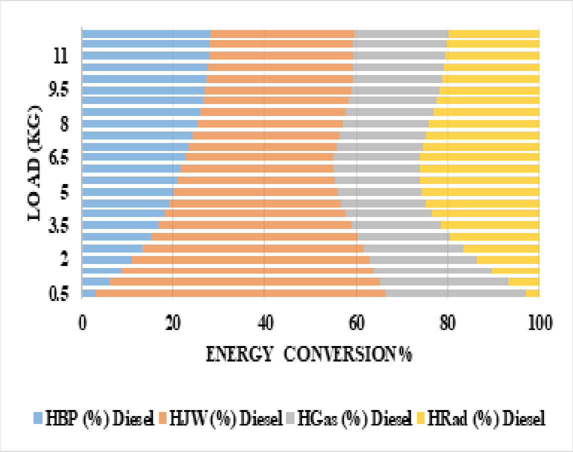

Figure 3: Heat Balance sheet of diesel

Figures 3-7 shows the energy conversion of diesel and blends of high-grade plastic oil at various loading conditions. It was found that, with the rise of load, heat conversion into useful work i.e., HBP increases. This is because of the high requirement of brake power with the rise of load. Heat in the jacket of cooling water decreases with the rise of load. Value of Heat loss in exhaust gas first decreases and at high load, the value

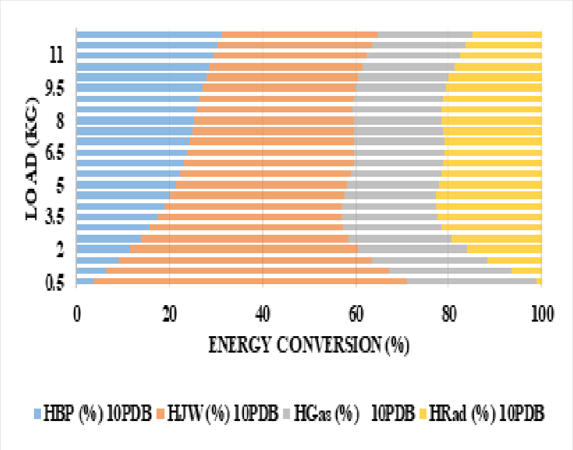

Figure 4: Heat balance sheet of 10 PDB

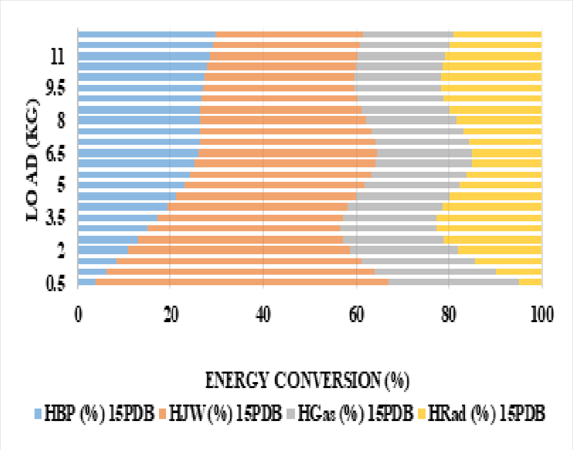

Figure 6: Heat balance sheet of 15 PDB

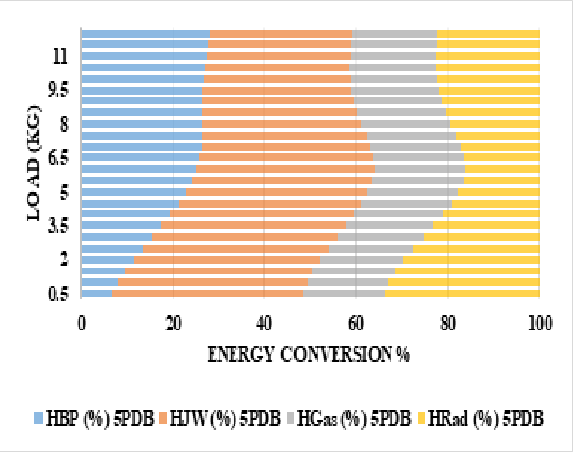

Figure 5: Heat balance sheet of 5 PDB

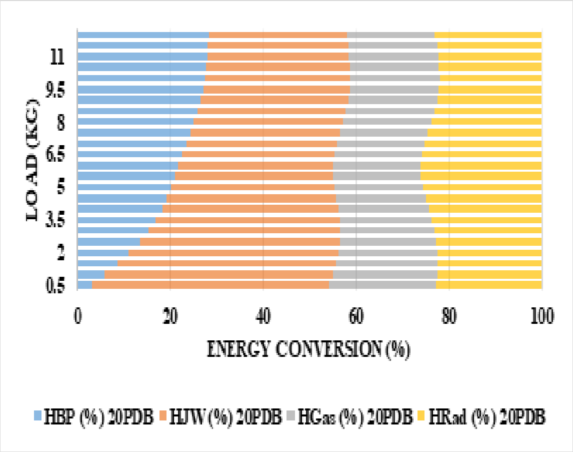

Figure 7: Thermal Balance sheet of 20 PDB

of loss through the exhaust increases. Value of heat loss through radiation (unaccounted heat) first increases and then decreases at a high load. The thermal balance sheet of blends of high-grade plastic oil and diesel is illustrated in Table 3.

From Figures 3-7, it was observed that %HBP for diesel varies from 3.31% to 28.14%, for 5PDB varies from 6.79% to 28.21%, for 10PDB varies from to 31.19%, for 15PDB varies from 3.94% to 29.86% and for 20PDB varies from 3.31% to 28.31% from low load to high load respectively. There seemed to be a minor difference in the value of % HBP. This is because blends of high-grade plastic fuel have high calorific value than diesel and due to shorter ignition delay, which reduces the pre-combustion mixture in the cylinder.

It was found that % heat loss through HJW for diesel varies from 63.25% to 31.35%, for 5PDB varies from 41.75% to 30.94%, for 10PDB varies from 67.05% and 33.47%, for 15PDB varies from 62.96% to 31.74% and for 20PDB varies from 50.96% to 29.74% from low load to high load. Heat loss through radiation for diesel varies from 30.56% to 20.76%, for 5PDB varies from 17.68% to 18.66%, for 10PDB varies from 27.97% to 20.46%, for 15PDB varies from 20.05% to 19.40% and for 20PDB varies from 23.05% to 19.00% from low load to high load respectively.

Remaining unaccounted heat in form of radiation for diesel varies from 2.88% to 26.11%, for 5PDB varies from 16.11% to 33.77%, for 10PDB varies from 1.11% to 22.78%, for 15PDB varies from 5.06% to 22.61% and for 20PDB varies from 21.94% to 26.11% from low load to high load respectively.

From Table 3, it can be observed that as the blending ratio of high-grade plastic oil with diesel increases, conversion of heat into useful work increases as compared to CI engine running on conventional diesel, this is due

Table 3: Thermal balance sheet of tested samples

	Load (%)	Diesel	5 PDB	10 PDB	15 PDB	20 PDB
Heat supplied (MJ/hr)	25	25.72	23.39	23.15	24.07	24.25
	50	34.60	28.15	30.76	28.50	33.72
	75	44.04	40.20	39.94	40.45	41.00
	100	49.51	49.86	45.04	47.88	51.49
HBP (%)	25	15.17	15.44	15.83	15.25	15.42
	50	21.79	25.30	23.13	25.33	21.79
	75	26.61	26.51	26.57	26.62	26.61
	100	28.14	28.21	31.19	29.86	28.31
HJW (%)	25	45.04	41.51	41.51	41.40	41.25
	50	33.32	36.45	36.45	38.93	33.29
	75	31.79	33.04	33.04	33.56	31.77
	100	31.35	30.94	33.47	31.74	29.74
HGas (%)	25	20.42	18.76	21.29	20.81	20.27
	50	18.79	19.93	19.39	20.65	18.80
	75	19.28	19.06	19.20	18.81	19.27
	100	20.76	18.66	20.46	19.40	19.00
HGas (%)	25	19.37	25.32	21.37	22.56	23.05
	50	19.37	16.11	21.03	15.09	26.11
	75	22.31	21.37	21.19	21.00	22.34
	100	19.75	22.21	14.89	19.00	22.96

to efficient combustion shown by the blends of high-grade plastic oil where low density and viscosity of blends of plastic oil help in better atomization of Air/Fuel ratio.

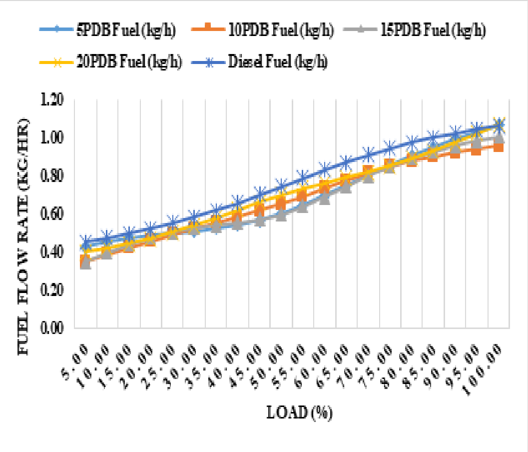

Figure 8: Fuel flow rate (kg/hr) Vs. Load (kg)

Figure 8 illustrates the rate of flow of blends of PDB with the load. It is observed that the fuel flow rate of diesel varies from 0.45Kg/hr to 1.06Kg/hr from low load to high load, 0.43 Kg/hr at low load to 1.06 Kg/hr at high load for 5PDB, 0.35 Kg/hr at low load to 0.96 Kg/hr at high load for 10PDB 0.35 Kg/hr at low load to 1.00 Kg/hr at high load for 15PDB and 0.40 Kg/hr at low load to 1.07 Kg/hr at high load for 20PDB. Diesel has a higher fuel flow rate than diesel, this is because of the lower calorific value of diesel. Relation of exhaust gas temperature of various blends of high-grade plastic fuel with % load as illustrated in Figure 9.

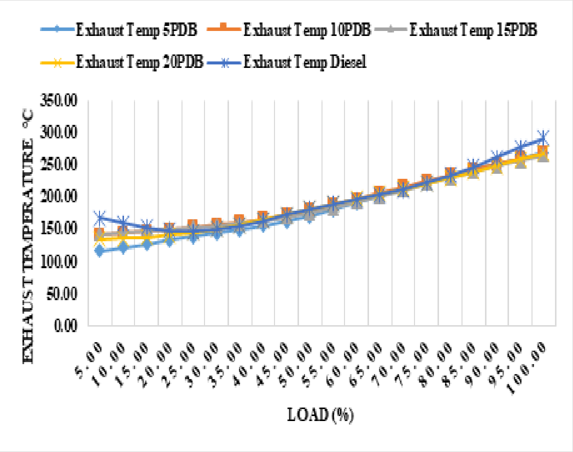

Figure 9: Exhaust gas temperature Vs. Load

Exhaust gas temperature of diesel varies from 166.77°C to 291.26°C, for 5PDB varies from 116.15°C to 268.0°C, for 10PDB varies from 141.07°C to 267.10°C, 15PDB varies from 141.98°C to 264.55°C and 20PDB varies from 133.36°C to 267.28°C. At low load, all the blends of PDB are lower than diesel this may be due to lower ignition delay of PDB and all the blends of PDB has higher calorific value than diesel which leader to proper burning of blends of PDB. Lower exhaust gas temperature of blends of plastic oil indicates the better conversion of heat energy produced in the cylinder into useful work.

4. Conclusion

Blends of high-grade plastic oil have a higher calorific value than that of diesel and the density and viscosity of blends of high-grade plastic oil are comparatively lower than that of diesel. The investigation was made to know the effect of these samples on the CI engine through a thermal balance sheet. The thermal balance sheet of blends of high-grade plastic oil with diesel is compared with diesel. It was found that all the blends of high-grade plastic oil with diesel showed a better conversion rate than that of diesel. The conclusion of the thermal balance sheet is as follows:

- All the blends of high-grade plastic fuel with diesel up to 20% by volume have relatively higher heat conversion into useful work i.e. HBP than diesel throughout the load.
- Exhaust gas temperature of blends of all high-grade plastic fuel has a lower value than diesel.

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