Indian Journal of Geo Marine Sciences
Vol. 49 (06), June 2020, pp. 1068-1077

Evaluation of DI engine operations at dual mode: biogas from *Tapioca sago* sludged poultry manure and tire oil blends

S Kesavan[a], R Sasikumar*[,b] & C Mohanraj[c]

[a]Department of Mechanical Engineering, SRG Engineering College, Namakkal – 637 017, India
[b]Department of Mechanical Engineering, Selvam College of Technology, Namakkal – 637 003, India
[c]Department of Mechanical Engineering, M. Kumarasamy College of Engineering, Karur – 639 113, India
*[E-Mail: sasikalipatty@gmail.com]

Received 20 June 2019; revised 24 July 2019

This article is focused to analyze the effects in engine operations when different alternative fuels jointly used. Normally biogas from pure sago sludge composed with Hydrogen sulfide (H_2S) which lead severe corrosion in engine parts. To reduce this effect, poultry manure (70 wt %) was mixed with sago sludge (30 wt %) for production of biogas. At maximum load, the brake thermal efficiency was found reduced up to 12 % with DTPO30 + biogas and 17 % with diesel + biogas compared to normal diesel operations. The brake specific fuel consumption was higher up to 10 % with distilled tire pyrolysis oil (DTPO30) with biogas operations than diesel with biogas. Reduced NOx about 27 % with DTPO30+ biogas and 21 % with diesel+ biogas than diesel operations. Correspondingly, increased CO was reported with dual fuel mode due to CO_2 presence with biogas. Also, increased hydrocarbon and reduced smoke opacity with biogas operations were reported. The H_2S effect on engine operation was reduced hence it can increase the engine reliability.

[**Keywords**: Biogas, Diesel engine, Poultry manure, Sago sludge, Tire oil]

Introduction

Automotive industries face lots of challenges with two major problems in which one was inflation in fossil fuels and adverse effects due to emissions from the automotive engine. Also, demand for hydro carbon fuel increases on a daily basis due to sophistication in life and industrialization. For these reasons, various alternative fuels were found and tested with an automotive engine to sustain the demand and inflation. Biogas is fuel gas produced from anaerobic digestion of any organic material such as animal waste, bird waste, human waste etc. Statistics reveal around 3000 metric tons (MT) of poultry manure per day is being produced by of hens at Namakkal, Tamil Nadu, India[1]. Also, lots of sago industries are located around the same region. Sago sludge wastewater and poultry manure were used to produce the biogas through an anaerobic digester. Among various alternative gaseous fuels, both mentioned biogases are preferred for clustered power production in rural regions. Some studies show sago wastewater was processed with civil construction for making concrete which has the same strength as normal concrete. This can reduce the water usages in construction[2]. Sago waste was processed with HUASB (hybrid up flow anaerobic sludge blanket) with a microorganism, and gas production rate was increased about 2.8 L/d compared to normal production 2.0 L/d[3]. Normally, biogas from sago sludge has more sulphur content, which results in severe impact on direct injection (DI) engine operations. The biogas from mixed sago waste sludge and poultry manure was used on DI engine as a primary fuel. This clustering or mixing of these sources reduces the impact of sulphur in sago sludge biogas during combustion. Biogas utilization on compression ignition (CI) engine has been the subject of extensive research work in the last decade. The mixture of biogas and air is ignited with the use of a minimum quantity of liquid fuel in CI engine and is referred to as dual fuel mode[4]. Also, liquid fuel is called pilot fuel and biogas as the primary fuel. Normally, biogas is composed of a maximum of methane and carbon dioxide. Sometimes less than 5 vol % of nitrogen, hydrogen and H_2S are also present in biogas; this mainly depends on raw materials used for digestion[5]. Biogas was produced using pure sago waste through anaerobic thermophilic digestion, and the composition of biogas was found 23 % of CO_2 and 74 % of methane with traces of H_2S(ref. 6). The sago starch was modified into OSA (octenyl succinic anhydride) to have better properties (both physicochemical and thermal) than its native state[7]. The biogas burns faster than liquid fuel and has lower emission which means eco-friendly and transportation through pipelines is possible when the corrosive components are removed[8]. The production cost of biogas is lower than other alternative fuel like producer gas, pyrolytic oil and biodiesel. As far as emission is concerned, comparatively biogas combustion emits higher CO_2 which can be neutralized by plants[9]. Use of biogas in diesel engine with diesel at dual fuel mode results in brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) being lower at medium loads, nitrous oxide (NOx) and particle matter in emission being reduced, ignition delay being longer and cylinder peak pressure being higher than the normal diesel operations[10]. Methane presence in biogas provides better resistance to knock effect due to high octane number and higher ignition temperature. Because of higher ignition temperature, it can be adopted with higher compression ratio operations with dual fuel mode in diesel engine[11]. Long term operation test has been carried out up to 2000 hours with biogas and diesel with dual fuel mode. This operation could achieve 90 % of biogas substitution and energy output has increased by 7 % with dual fuel compared with normal diesel operations. A thin layer of carbon deposition has been found after long-duration test with dual fuel. Other than carbon deposition, no other adverse effect has been found including wear[12].

Another possible source chosen for alternative fuel was tire scraps which are largely available from automotive workshops in our region. On a daily basis, there were 5 MT of tire scraps thrown in an environment which cannot be recycled in Namakkal municipality corporation, Tamil Nadu, India. Currently, several methods are being used for disposing the tire such as recycling, reusing, waste to energy etc. The used tires are utilized in many ways like the stabilizer, sound barrier, vibration damper, extraction of carbon products, surface mats for playgrounds etc. Maximum volume of tire scraps have undergone recycling process, with the rest of them being directly dumped into an environment which causes many adverse effects such as various types of pollution, diseases related with generation of mosquitoes etc. Beyond those approaches, another possibility is extraction of fuel from tire through pyrolysis process[13]. Normally pure TPO (tire pyrolysis oil) has a higher viscosity, sulphur, carbon blocks and acid value which affect the engine performance and life[28]. Because of these adverse effects, TPO has undergone desulphurization and distillation to remove the carbon blocks, also decrease the sulphur and acid values. The desulphurized and distilled TPO with diesel blends were tested in DI engine without modification. The results have shown that the increased cylinder pressure read up to 1.6 bar with TPO80 from normal diesel operations. Also, brake thermal efficiency increased with the increase of TPO blends. Ignition delay has been longer with TPO blends operations. Lowered NOx and increased HC, CO and smoke have been noticed compared with diesel[10]. Another study has been done with dual fuel mode using producer gas and used vegetable oil methyl ester. The result has shown slighter decrease in thermal efficiency, longer ignition delay and reduced smoke opacity with producer gas and vegetable oil methyl ester blends than diesel[14]. This is a modest try to combine two different phase of alternate fuel together and applied on DI engine utilization.

This work mainly focused on the evaluation operational parameters of DI engine when it runs at multi- fuel mode using two different alternate fuels. Biogas was a primary fuel which was produced from mixed poultry manure and sago sludge, then distilled tire oil blends as pilot fuel. Normally biogas from *Tapioca sago* has more hydrogen sulfide than poultry and other biogases, which leads to severe corrosion in engine parts. To reduce this effect, tapoica sago sludge was mixed with poultry manure before digestion. Initially proximate and ultimate analysis were carried out for raw poultry manure and mixed sago sludge with poultry manure. After gas obtaining, the CH_4 and CO_2 composition were monitored for all the samples. The fuel properties were recorded and compared with pure diesel fuel. The engine performance, combustion and emissions were obtained with different samples and results were compared with each of the other samples.

Materials and Methods

Biogas preparation

The biogas was obtained using continued stirring tank reactor (CSTR) separately and collected in the bladder through a compressor. Table 1 and Table 2 give the results of the proximate and ultimate analysis of poultry manure, sago sludge treated poultry manure. The volatile content and gross calorific values dropped down slightly while the addition of sago sludge with poultry manure. The sago sludge mixed poultry manure consists of 70 wt % of poultry manure and 30 wt % of sago sludge. Instead of pure sago sludge digestion which causes high H_2S production, the mixing of poultry manure with sago sludge can reduce the composition of H_2S in biogas. Further, it helps to utilize the sago sludge effectively without major adverse effects in engine parts. In case of increasing the poultry manure by more than 70 wt % in this mixing result in the reduction in utilization of sago sludge, and increasing the sago sludge about more than 30 wt % produces more H_2S in biogas. The gas obtained from mixed sago sludge and poultry manure was tested with DI engine at dual-fuel mode.

Table 1 — Proximate analysis of different samples

	Moisture %	Volatile matter %	Fixed Carbon %	Gross calorific value kJ/kg
Poultry manure (hens)	27.40	52.8	5.2	9321.952
Sago sludge treated poultry manure	38.87	49.34	4.3	8257.136

Table 2 — Ultimate analysis of different samples

	Carbon %	Hydrogen %	Oxygen %	Nitrogen %	Sulphur %	Ash content %
Poultry manure (hens)	38.8	9.3	8.7	6.5	1.4	25.5
Sago sludge treated poultry manure	31.05	7.4	6.9	4.3	1.8	18.16

Tire oil preparation

The waste tire scraps were collected from automotive workshops and cut into small chips. The 150 mm diameter and 300 mm height of fixed bed pyrolysis reactor was utilized for obtaining the oil. The 2 kW copper coil was wound around the reactor and it was connected with PID controller. Along with this a K type thermocouple was fixed to measure the reaction temperature. The counter flow condenser was attached with the reactor which was used to condense the tire vapour coming out from the pyrolysis reactor. The maximum conversion rate was noted to be about 62 % to 71 %. After the extraction of the oil, it was distilled through a fractional distillation column. The temperature was set between 145 °C and 280 °C. The entire set of extraction and distillation unit is shown in Figure 1. The optimized blending was found to be DTPO30 (30 % blends of Distilled tire pyrolysis oil with diesel) through various experimentations with similar operating conditions[15].

The properties of virgin DTPO, DTPO30 and diesel are given in Table 3.

Engine set-up

The whole engine testing set-up is shown in Figure 2. The single-cylinder, constant speed and water- cooled engine was utilized for conducting experiments. The compressed biogas was filled in the bladder and connected with air intake line. The different flow sensors were attached for both air and

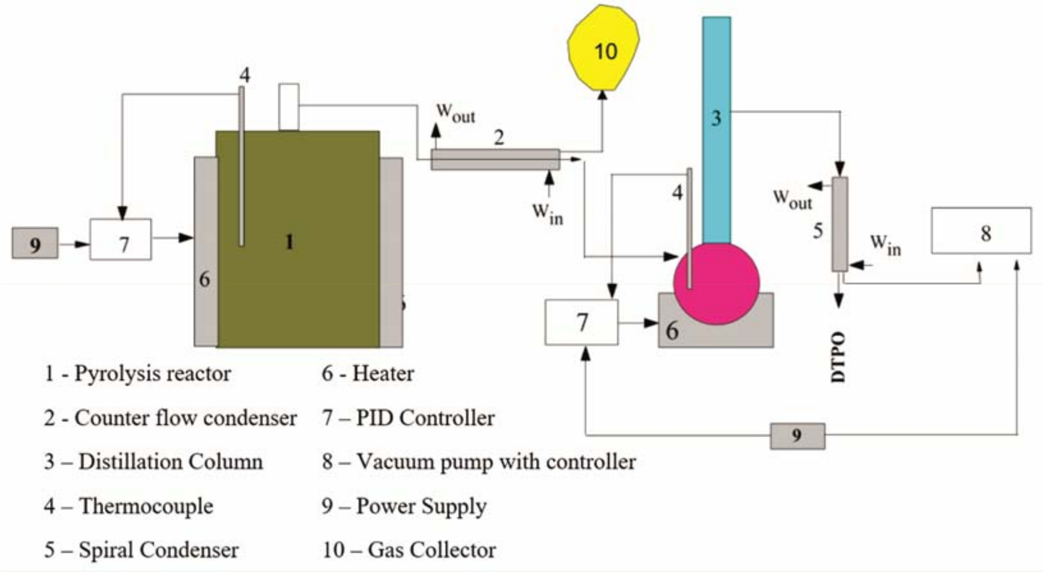

Fig. 1 — Schematic diagram for tire oil extraction and distillation set-up

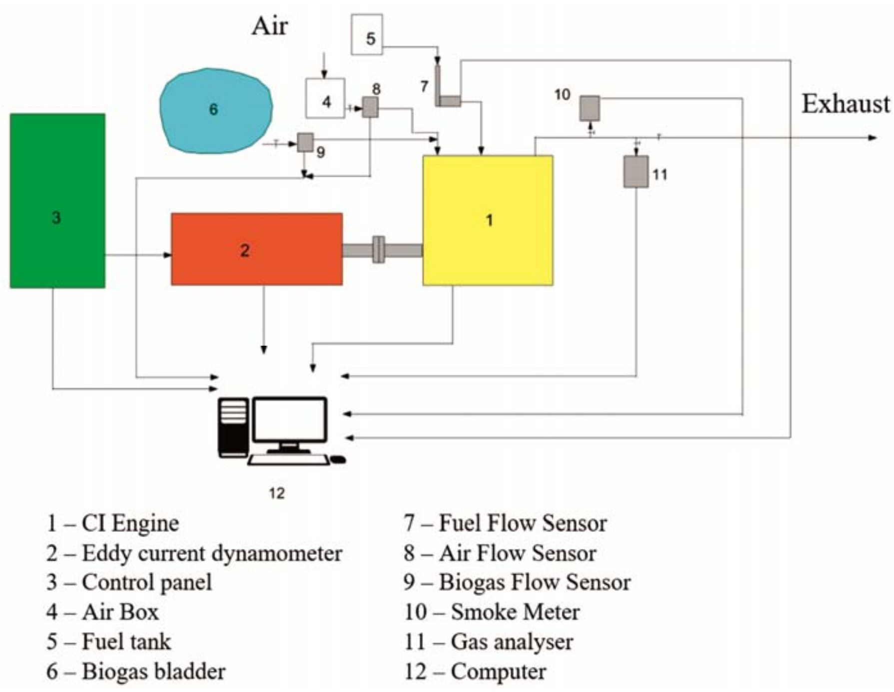

Fig. 2 — Experimental set-up

Table 3 — Properties of various fuel samples

	Density kg/m^3	Kinematic viscosity CST	Gross calorific value in kJ/kg	Flash Point °C	Fire Point °C	Acid Value	Sulphur Content in %	Cetane number
Testing Methods	IS 1448 P 32	IS1448P25	Bomb colorimeter	IS 1448 P 69	IS 1448 P 69	IS 1448 P2	IS 1448 P 33	IS 15607 : 2005
Diesel	832	3.05	46346.12	50	56	0.5	0.045	55
TPO	976	2.9	41789	43	48	4.3	0.87	49
DTPO	864	1.01	44091.09	34	43	3.56	0.34	41
DTPO30	858	2.02	45276.6	43	49	3.01	0.12	50

biogas with regulator value. The specification of engine set-up is given in Table 4. The optimized blend for distilled tire oil with diesel is 30 vol % (DTPO30) and the optimized biogas flow rate was fixed at 0.9 kg/h. Also, the values of uncertainties with various equipments are given in Table 5. The maximum percentage of uncertainty of the experiment was obtained by equation 1. Using the values from Table 5 in equation 1, the sum of uncertainties was obtained as ± 1.99.

$$U = \sqrt{\sum_{i=1}^{n} X_i^2} \qquad \ldots (1)$$

Result and Discussions

Methane and Carbon dioxide

Figure 3 indicates the presence of CH_4 and CO_2 in biogas obtained from raw poultry manure, raw sago sludge and mixed sago sludge water with poultry

Table 4 — Engine Specifications

Specifications	Kirloskar, single cylinder, 4 stroke, air cooled and CI engine with 661 cc
Cylinder bore in mm	87.5
Stroke length in mm	110
Rated power output in kW	5.2 with 1500 rpm
Compression ratio	17.5:1
Injection pressure in bar	200
Injection timing °CA	23
Fuel	H.S. diesel
Dynamometer arm length in mm	185 mm arm length, eddy current, water cooled.
Piezo sensor	Range 5000 PSI, with low noise cable
Crank angle sensor	Resolution 1 Deg, Speed 5500 RPM with TDC pulse.
Data acquisition device	NI USB-6210, 16-bit, 250kS/s.
Temperature sensor	Type RTD, PT100 and Thermocouple, Type K
Load sensor	Load cell, type strain gauge, range 0-50 Kg
Fuel flow transmitter	DP transmitter, Range 0-500 mm WC
Air flow transmitter	Pressure transmitter, Range (-) 250 mm WC

manure. The maximum methane obtained with raw poultry manure gas (RPMG) was about 23.8 % compared with both raw sago sludge gas (RSBG) about 22 % and mixed sago poultry manure gas (MSPMG) about 23 %. Likely the CO_2 with RSBG was higher by about 9.9 % than both RPMG (8 %) and MSPMG (8.2 %). For this investigation, mixed sago poultry manure gas was utilized.

Table 5 — Equipment with uncertainties

Instrument	Uncertainty in %
Pressure transducer (Cylinder pressure)	±1
Crank angle encoder	±0.2
Load cell (Strain gauge)	±0.2
Speed sensor	±0.1
Thermocouple K type	±0.15
Fuel flow sensor	±0.5
Air flow sensor	±0.5
AVL digas analyzer CO_2	±1
CO	±0.3
HC	±0.1
O_2	±0.15
NOx	±0.5
AVL smoke meter-Smoke opacity	±1

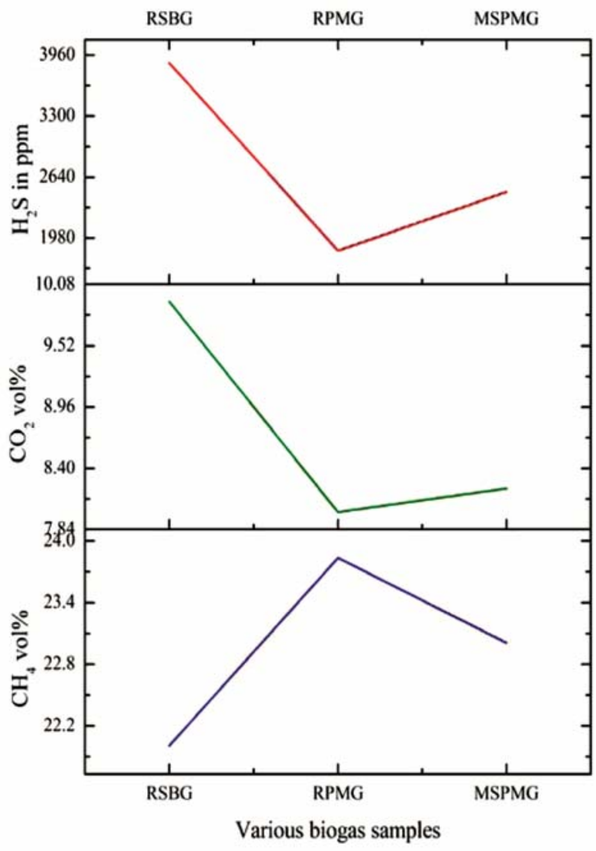

Fig. 3 — Gas Chromatogram of raw sago sludge bio gas (RSBG), raw poultry manure gas (RPMG) and mixed sago sludge, poultry manure gas (MSPMG)

The higher CH_4 with poultry manure gas is due to more carbon and hydrogen contents than sago sludge, which is shown in Table 2. The CH_4 positively influenced the gross calorific value of biogas. The biogas with better calorific value can reduce the pilot liquid fuel usages. Normally, RSBG has lower calorific value and higher H_2S content which are the causes of higher liquid fuel consumption and severe corrosion respectively. But MSPMG has good caloric value with reduced H_2S content which is adaptable for DI engine operations referred to in Table 3.

Performance studies

The performance parameters have been observed with dual fuel mode (diesel with biogas and DTPO30 with biogas), diesel and tire only mode. The results have been compared and discussed below.

Brake thermal efficiency (BTE)

The variations of BTE are shown in Figure 4(a). The BTE is higher with diesel as compared to DTPO30 due to lower calorific value and lower cetane number of tire oil. Furthermore, diesel with biogas is higher than DTPO30 with biogas at dual-fuel mode.

The BTEs with diesel and DTPO30 are about 21.53 % and 19.77 % at low load, 37.38 and 35.87 % at

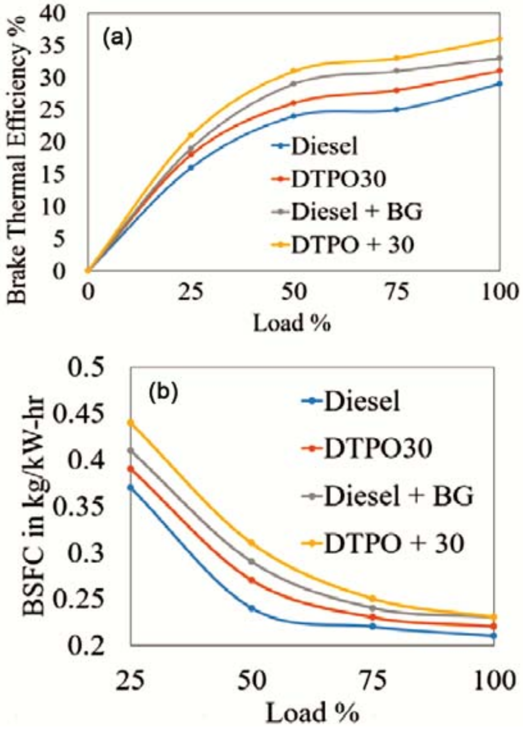

Fig. 4 — Variations of: (a) BTE with loads, and (b) BSFC with loads

high load, respectively. At dual fuel mode, the BTE has been observed to be about 16.55 % with (DTPO30+biogas) and 18.01 % with (diesel+biogas) at lower load. During maximum load, it has been observed to be 34.76 % with (diesel + biogas) and 32.78 % with (DTPO30+biogas). Presence of biogas with air has led to reduction in the BTE due to its residual presence, lower burning temperature, low velocity of flame propagation and lower calorific values[16]. In addition to these factors, deficiency of oxygen causes lower conversion efficiency of input fuel into energy, especially with lower loads. Moreover, lower conversion efficiency leads to increase in the fuel flow rate during combustion[17].

Brake specific fuel consumption

The variation of BSFC is shown in Figure 4(b). Obviously, the BSFC with dual fuel mode is higher than single fuel mode (diesel and DTPO30). This is due to lower density, decreased cylinder temperature and maximum CO_2 presence with biogas[18].

The BSFC with diesel has been noted to be about 0.39 and 0.21 kg/kWhr at lower and maximum loads, whereas the values obtained for diesel with biogas are 0.43 and 0.22 kg/kWhr. BSFC with DTPO30 has been recorded to be about 0.44 and 0.215 kg/kWhr at low and high loads. DTPO30 with biogas has been reported to be about 0.47 and 0.225 kg/kWhr at low and high loads, respectively. From these investigations, it becomes clear that the differences of BSFC between various samples at lower loads are higher than high loads because of increased cylinder temperature at higher loads[19].

Combustion parameters

Cylinder pressure

The cylinder pressure was found maximum at higher loads for all the samples. At lower loads, the engine runs with lean mixture which affects the pre-ignition reactions. The pressure inside the cylinder with dual fuel (diesel with biogas) found higher than diesel only operation due to earlier combustion caused by biogas addition.

Figure 5(a) shows the peak pressure occurred later with dual fuel (diesel with biogas) in comparison with diesel due to ignition delay. The ignition delay has been caused by increased CO_2 presence and higher specific heat of biogas. The peak pressure with diesel is about 68.212 bar at 10° CA, whereas it is 69.345 bar at 12° CA for dual fuel (diesel with biogas). Similarly, DTPO30 has recorded about 69.567 bar at 12° CA, whereas at 13° CA for dual fuel (DTPO30 with biogas). Larger fluctuations in maximum have been found with TPO blends between 0° CA and 20° CA. This is mainly because of non-homogeneity in fuel mixture. Also, peak pressure has been found to be higher with TPO blends than diesel fuels. The ignition delay has been noted to be about 2, 3, and 4° CA for diesel with biogas, DTPO30, and DTPO30 with biogas, respectively.

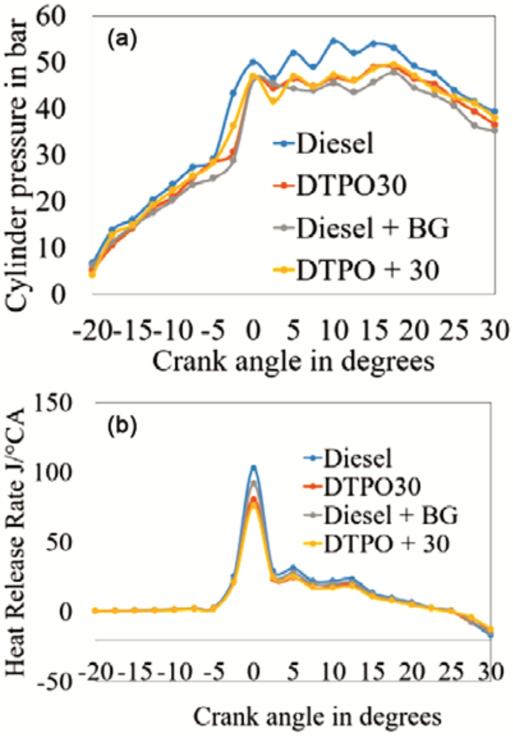

Fig. 5 — (a) Cylinder pressure variations with crank angle at full load, and (b) Net heat release rate with crank angle at full load

Net heat release rate

The heat release rate mainly influenced ignition delay, combustion rate and mixture preparation during initial stage of combustion[20]. The maximum heat release rate was lower with single fuel mode (both diesel and DTPO30) than dual fuel mode; this was because of higher fuel accumulation caused by ignition delay and combustion effect of combined liquid and gases fuel[21].

Also the maximum heat release rate was found at delayed time with dual fuel mode rather than at single fuel mode; this was because of CO_2 presence and high specific heat of biogas. Figure 5(b) shows the maximum heat release rate with diesel to be about 73.51 J/° CA at -1° CA, whereas 83.61 J/° CA at 1° CA with diesel with biogas. In addition, DTPO30 recorded about 110.08 J/° CA at 1° CA whereas 115.43 J/° CA at 2° CA with DTPO30 with biogas.

Emission analysis

Oxides of Nitrogen (NO_x)

The NO_x formation in emission highly depended on cylinder temperature and stoichiometry of mixture[22]. The lean mixture led to decreasing the cylinder temperature which causes the lower NO_x formation. The concentration of NO_x with single fuel mode was higher than dual fuel mode for all the loads; this was because of CO_2 presence with biogas which has higher specific heat.

The higher specific heat can reduce the cylinder temperature, thereby lowering NOx. In addition to that, lower cylinder temperature occurred due to lesser concentration of oxygen with biogas[23]. In Figure 6(a), the NO_x was noted with diesel to be about 81 ppm at lower load and 2480 ppm at full load, whereas 51 ppm at lower load and 2048 ppm at full load for diesel with biogas operations. DTPO30 reported about 76 ppm at low load and 2735 ppm at full load while DTPO30 with biogas recorded about 42 ppm at low load and 1945 ppm at full load.

Carbon monoxide (CO)

The CO presence in emissions may indicate the incomplete combustion. Figure 6(b) shows the CO emission being higher with biogas operations than single fuel operations for all the conditions; this is due to CO_2 presence and short of oxygen which help to

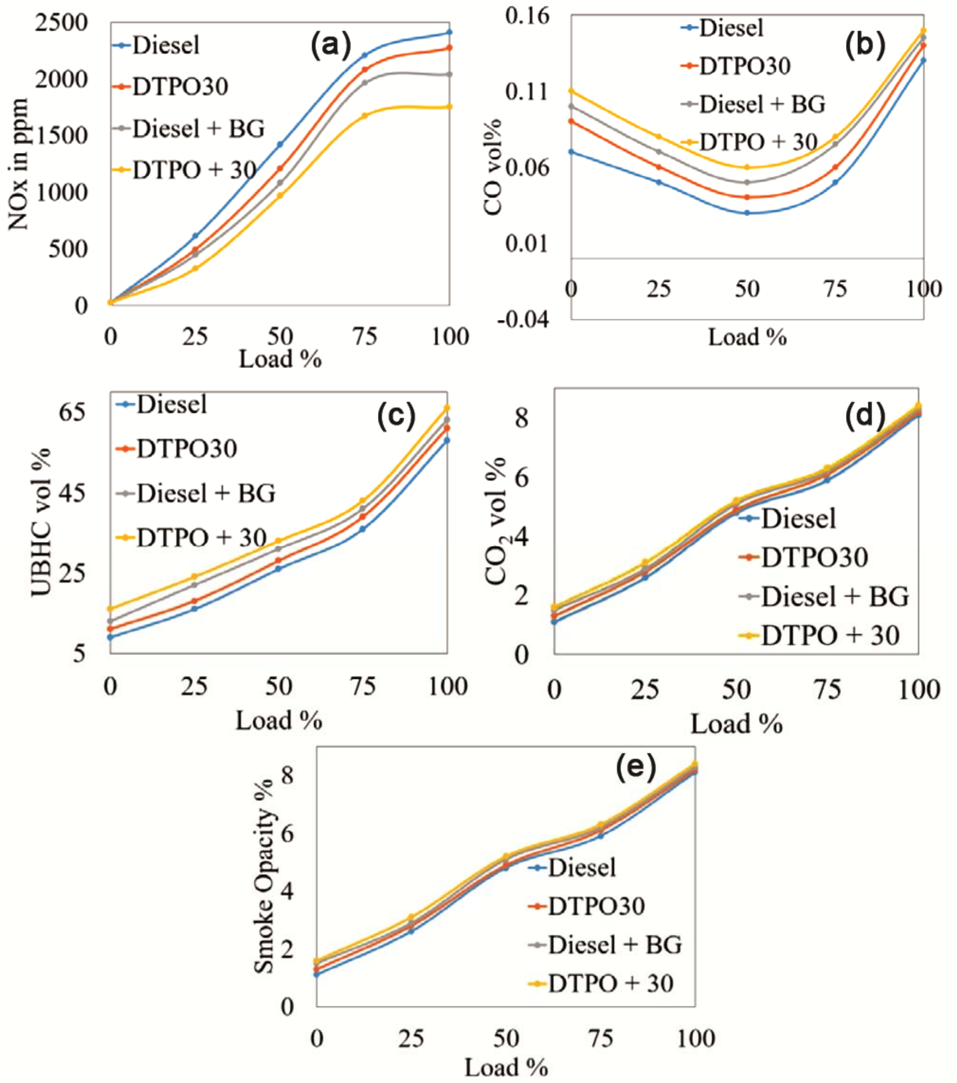

Fig. 6 — Variation of: (a) NO_x formation with loads, (b) CO formation with loads, (c) UBHC formation with loads, (d) CO_2 formation with loads, and (e) Smoke Opacity with loads

convert CO into CO_2 during combustion. Biogas with more CO_2 led to suppress the flame around pilot fuel[24].

The CO with diesel varied from 0.072 vol % at low load to 0.136 vol % at high load, whereas 0.097 vol % at low load to 0.168 vol % at high load for diesel with biogas. DTPO30 varied between lower and maximum load as 0.079 vol % and 0.142 vol %, while DTPO30 with biogas reported between 0.101 and 0.172 vol % for low and high loads, respectively. From these investigations, it was clear that DTPO30 had higher CO concentration with emission than diesel due to lean mixture found nearer to walls where flame could not propagate. Due to this, combustion was not carried out completely[25].

Unburnt hydrocarbon (UBHC)

In addition to CO, the UBHC presence in emission also indicated incomplete combustion. Figure 6(c) shows DTPO30 having higher than diesel values. The UBHC with DTPO30 has been noted to be about 20 ppm at low load and 61 ppm at high load while the diesel produced about 16 ppm at low load and 59 ppm at high load. This is due to DTPO30 blends not having propagated deeper into the combustion zone and some of the hydrocarbon having stayed nearer to the cylinder wall and crevice volume being left unburned[26].

Moreover, an engine with biogas produced higher UBHC than single fuel mode. This was because of biogas flow at inlet that led to reduce the oxygen and increase the CO_2 which was the cause of UBHC. In addition to that, air-biogas mixture was urged into crevice volume during the compression stroke and then remained unburned[21]. The UBHC with (Diesel + Biogas) recorded about 23 ppm at low load and 64 ppm at high load, whereas using DTPO30 with biogas produced about 28 ppm at load and 68 ppm at high load.

Carbon dioxide (CO_2)

Figure 6(d) shows the variations of CO_2 contents with emission for different operations. Emission with higher CO_2 indicates complete and better combustion. The diesel had higher CO_2 emissions than DTPO30; this was because of lesser combustion duration. Also, lower volume of CO_2 with emission was found with biogas operations than single fuel mode because of short of oxygen and so CO could not be converted into CO_2. The CO_2 emission with DTPO30 was recorded to be about 1.45 vol % at low load and 9.086 vol % at high load. The DTPO30 with biogas emitted about 1.24 vol % at low load and 8.52 vol % at high load.

Smoke opacity

Figure 6(e) shows the smoke opacity with DTPO30 being higher than diesel fuel at single fuel mode. The reasons behind this were higher aromatic content with tire oil, longer ignition delay and higher UBHC. At dual fuel mode, the opacity was lower than single fuel mode; it was due to biogas flow which replaced some quantity of diesel that eventually resulted in lower smoke emission. In addition to that, the formation of smoke influenced cylinder temperature which strongly depended on aromatic content and the quantity of oxygen inside the cylinder.

The smoke opacity with diesel was noted to be about 5.5 % at low load and 62 % at high load, whereas it was about 4.3 % at low load and 55.78 at high load with the use of diesel with biogas. In respect of this, DTPO30 was recorded to be about 9.3 % at low load and 69.2 % at high load while DTPO30 with biogas produced about 7.8 % at low load and 64.38 % at high load.

Conclusions

From these experimental investigations, it is evident that the engine can run with DTPO and biogas. The optimized flow rate of biogas was fixed as 0.9 kg/hr because of larger CO_2 and Sulphur present in the biogas that led to higher corrosion respectively. Beyond 30 vol % of DTPO, more engine vibrations, incomplete combustion which turns to get engine off at higher engine loads. This is due to non-homogeneity of fuels leads improper mixing during combustion which causes of combustion instability especially with higher loads. The production of H_2S with mixed sago sludge and poultry manure was reduced up to 56 % than raw sago sludge which results in lower corrosion effect on DI engine. Compared with diesel operations, BTE was lowered up to 12 % and 20 % for diesel + biogas and DTPO30 + biogas, respectively, the lower BTE with tire oil operations is because of low energy content and lower calorific value of the tire oil. BSFC was found higher with DTPO30+biogas up to 10 % than diesel+biogas. Cylinder pressure and peak pressure were little higher for DTPO30 with biogas about 69.567 bar than for diesel with biogas about 68.345; this was due to ignition delay caused by non-homogeneity of fuel and lower cetane number which led to improper mixing.

Longer ignition delay was observed for DTPO30 with biogas. At higher maximum loads, NOx in emission was found lower up to 7 % for DTPO30 with biogas than for diesel with biogas. This was due to aromatic contents presence with tire oil and delayed combustion. UBHC and CO were higher up to 8 % and 7 % for DTPO30 with biogas than for diesel; this was due to later combustion, lean mixture, lower cylinder temperature and unsaturated hydrocarbon. Smoke intensity got better reduced up to 11 % with diesel+biogas operations than diesel operations; this was because of delayed combustion, insufficient oxygen and replacement of liquid fuel by biogas. But smoke intensity with DTPO30+biogas was found higher up to 12 % than diesel operations. On the whole, utilization of biogas with DTPO on DI engine operations provide desirable results, saving petroleum diesel and to utilize biomass, tire scraps together. It is also promising technique for electricity generation by clustering of sago industries and poultry form with reduced H_2S effect.

Abbreviations

DI – Direct injection
TPO – Tire pyrolysis oil
DTPO – Distilled tire pyrolysis oil
CSTR – Continuous stir tank reactor
RPMG – Raw poultry manure gas
RSBG – Raw sago sludge biogas
MSMG – Mixed sago poultry manure gas
DTPO30 – Distilled tire pyrolysis oil (30 vol % of distilled tire oil with 70 vol % diesel)

Acknowledgements

The authors would like to acknowledge the help extended by Dr. R. Mohan, Associate Professor, Department of Mechanical Engineering, Sona College of Engineering, Salem – 636 005 and Dr. S. Suresh, Assistant Professor, Department of Mechanical Engineering, National Institute of Technology for their continuous support in the research paper.

Conflict of Interest

Authors have declared that there is no conflict of interest.

Author Contributions

This work has been carried out by SK: Conducted literature survey, identified the research gap, and conducted the experiments; RS: Guidance to SK and helped in proper structuring of the research paper; and CM: Assisted in structuring of the research paper.

References

1 Stalin J S D, Tamil Nadu firm produces electricity using poultry waste, World Wide Web electronic publication, http://www.ndtv.com, version 07/2013.

2 Muniraj K, Asha B, Swaminathan P & Sekar B, Reuse of sago treated wastewater partially substitute in concrete, *Int J Appl Eng Res*, 10 (2) (2015) 2505-2512.

3 Priya M, Meenambal T, Balasubramanian N & Perumal B, Comparative study of treatment of sago wastewater using HUASB reactor in the presence and absence of effective microorganisms, *Procedia Earth Planet Sci*, 11 (2015) 483-490.

4 Yoon S H & Lee C S, Experimental investigation on the combustion and exhaust emission characteristics of biogas–biodiesel dual-fuel combustion in a CI engine, *Fuel Process Technol*, 92 (5) (2011) 992-1000.

5 Bedoya I D, Arrieta A A & Cadavid F J, Effects of mixing system and pilot fuel quality on diesel–biogas dual fuel engine performance, *Bioresour Technol*, 100 (2009) 6624-6629.

6 Mohan S, Vidhya K, Sivakumar C T, Shanmugavadivu V & Kumaresh M, Production of biogas by using anaerobic sludge digestion of sago waste, *Natl J Multidiscip Res Dev*, 3 (1) (2018) 1147-1154.

7 Abiddin N Z, Yusoff A & Ahmad N, Effect of octenylsuccinylation on physicochemical, thermal, morphological and stability of octenyl succinic anhydride (OSA) modified sago starch, *Food Hydrocoll*, 75 (2018) 138-146.

8 Tippayawong N & Thanompongchart P, Biogas quality upgrade by simultaneous removal of CO_2 and H_2S in a packed column reactor, *Energy*, 35 (12) (2010) 4531-4535.

9 Fatih D M, Balat M & Balat H, Biowastes-to-biofuels, *Energ Convers Manage*, 52 (4) (2011) 1815-1828.

10 Chandra R, Vijay V K & Subbarao P M V, Performance evaluation of a constant speed IC engine on CNG, methane enriched biogas and biogas, *Appl Energy*, 88 (2011) 3969-3977.

11 Debabrata B & Murugan S, Simultaneous reduction of NO_x and smoke in a dual fuel DI diesel engine, *Energ Convers Manage*, 84 (2014) 217-226.

12 Sahoo B B, Sahoo N & Saha U K, Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines—A critical review, *Renew Sust Energ Rev*, 13 (6-7) (2009) 1151-1184.

13 Mohanraj C, Senthilkumar T & Chandrasekar M, A review on conversion techniques of liquid fuel from waste plastic materials, *Int J Energy Res*, 41 (2017) 1534-1552.

14 Murugan S, Ramaswamy M C & Nagarajan G, Performance, emission and combustion studies of a DI diesel engine using Distilled Tyre pyrolysis oil-diesel blends, *Fuel Process Technol*, 89 (2008) 152-159.

15 Balakrishnan N, Mayilsamy K & Nedunchezhian N, An Investigation of the Performance, Combustion, and Emission Characteristics of a CI Engine Fueled with Used Vegetable Oil Methyl Ester and Producer Gas, *Int J Green Energy*, 12 (2015) 506-514.

16 Yoon S H, Park S H & Lee C S, Experimental Investigation on the Fuel Properties of Biodiesel and Its Blends at Various Temperatures, *Energ Fuel*, 22 (1) (2008) 652–656.

17 Cacua K, Amell A & Cadavid F, Effects of oxygen enriched air on the operation and performance of a diesel-biogas dual fuel engine, *Biomass Bioenerg*, 45 (2012) 159-167.

18 Paul A, Panua R S, Debroy D & Bose P K, Effect of compressed natural gas dual fuel operation with diesel and Pongamia pinnata methyl ester (PPME) as pilot fuels on performance and emission characteristics of a CI Engine, *Energy*, 68 (2014) 495-509.

19 Devan P K & Mahalakshmi N, Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels, *Fuel Process Technol*, 90 (2009) 513-519.

20 Heywood J, Internal combustion engine fundamentals, (McGraw Hill Publications) 1988, pp. 491-500.

21 Mustafi N N, Raine R R & Verhelst S, Combustion and emissions characteristics of a dual fuel engine operated on alternative gaseous fuels, *Fuel*, 109 (2013) 669-678.

22 Nagarajan G, Rao A N & Renganarayanan S, Emission and performance characteristics of neat ethanol fuelled DI diesel engine, *Int J Ambient Energy*, 23 (2002) 149-158.

23 Saravanan S, Nagarajan G, Anand S & Sampath S, Correlation for thermal NO_x formation in compression ignition (CI) engine fuelled with diesel and biodiesel, *Energy*, 42 (2012) 401-410.

24 Papagiannakis R G, Kotsiopoulos P N, Zannis T C, Yfantis E A, Hountalas D T, *et al.*, Theoretical study of the effects of engine parameters on performance and emissions of a pilot ignited natural gas diesel engine, *Energy*, 35 (2010) 1129-1138.

25 Murugan S, Ramaswamy M C & Nagarajan G, Assessment of pyrolysis oil as an energy source for diesel engines, *Fuel Process Technol*, 90 (1) (2009) 67-74.

26 Karim G A, A review of combustion processes in the dual fuel engine—The gas diesel engine, *Prog Energy Combust Sci*, 6 (3) (1980) 277-285.