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Improved Cold Flow Properties and Combustion Analysis of High Viscous Castor Oil and its Biodiesel in a CI Engine

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ABSTRACT

Vegetable oils are desirable as alternate fuels with ignition quality equivalent to diesel and its combustion characteristics, but unsuitable for direct operation in compression ignition (CI) engines as fuel because of their high viscosity in nature. Hence, fuel and engine based modifications are being tried to improve the performance of the CI engines. The high viscous oil does not evaporate quickly even after it is injected into the hot combustion chamber. Therefore, converting the high viscous vegetable oil into biodiesel improves the evaporation and hence combustion. There are two major problems related to the use of biodiesel as fuel are its oxidation stability and cold flow performance. In this investigation, castor oil, having a very high viscosity of 226.2 cSt at ambient temperature, is used as a fuel. The test results show a significant increase in the brake thermal efficiency from 23.5% (neat castor oil) to 29.7% with castor oil biodiesel (COME) operation. CO and HC emissions of the engine are less with castor oil biodiesel. The smoke emission reduces marginally with castor oil biodiesel to 69% at full load, but it is still higher than diesel fuel 57%.

INTRODUCTION

The inventor of diesel engine, Rudolf Diesel confidently predicted that the plant-based oils would be widely used to operate the engine. Vegetable oils can be used as an alternative fuels for compression ignition engines. These fuels are renewable and sulphur free. In this regard, vegetable oils can be a partial replacement for diesel oil with small modifications, which forms the basis for our transportation and agricultural operations. Extensive research in the last three decades in using edible oil (Singh et al. 2010, Bari et al. 2002, Canakci et al. 2009, Hürdogan et al. 2016 and Agarwal et al. 2010) non-edible oil (Agarwal et al. 2007, Thiyagarajan et al. 2016, Sureshkumar et al. 2008, Nabi et al. 2009, Dhananmurugan et al. 2015 and Geo et al. 2008) and oil extracted from wastes such as waste fat, waste cooking oil, waste coffee grounds and algae (Altun et al. 2016, Kumar et al. 2014, Kumar et al. 2005 and Demirbas et al. 2011) for diesel engines have been carried out, and performance, combustion and emission data have been reported in detail. However, not much attention was focused on high viscous, non-edible oils such as castor oil as an engine fuel. Engine research in a single cylinder CI engine with neat castor oil and its biodiesel with or without blending diesel have been carried out to a limited extent (Ghanei et al. 2015, Wander et al. 2011 and Dias et al. 2013). However, the combustion behavior of neat castor oil and its biodiesel have not been reported in detail.

Scholz et al. (2008) studied the prospects and risks on the use of castor oil as an engine fuel, which was supported by the German Society for Technical Cooperation and National Council for Scientific and Technological Development, Brazil. They found that NCO had several properties, in particular, the extremely high viscosity and the water content complicated the use of castor oil as straight vegetable oil in engines and despite the unfavourable engine related technical properties of straight castor oil, it was possible to produce a methyl or ethyl ester by transesterification which could be possibly added to diesel fuel in small proportions. Panwar et al. (2009) tested the castor oil methyl ester (COME) for emission characteristics in a four-stroke single cylinder CI engine at a constant speed of 1500 rpm at different loads for 5%, 10% and 20% biodiesel blends with diesel. They reported that with increasing biodiesel percentage in the fuel blend, CO and smoke emissions were found to be reduced and CO_2 and NO_x emissions were marginally higher.

Valente et al. (2010) investigated the impacts on fuel consumption and exhaust emissions of a diesel engine powered generator operating with COME-diesel blends. Fuel blends containing 5%, 20% and 35% of COME with diesel oil were tested by varying the engine load from 9.6 kW to 35.7 kW. Their results showed that there was an increase in fuel consumption with higher biodiesel concentration in the COME-diesel fuel blend. At low and moderate loads,

Table 1: Chemical composition of castor oil.

Name of the acid	Percentage
Ricinoleic acid	89.5
Linoleic acid	4.2
Oleic acid	3
Stearic acid	1
Palmitic acid	1
Dihydroxystearic acid	0.7
Linolenic acid	0.3
Eicosanoic acid	0.3

with 35% COME in the blend, CO emission was increased by 40%. At the low output of 9.6 kW, the use of fuel blend containing 20% of COME increased HC emissions by 16%. Exhaust CO_2 concentration did not change significantly.

Panwar et al. (2010) experimented with various COME percentage blend with diesel in a four stroke, single cylinder variable compression ratio diesel engine at a rated speed of 1500 rpm at different loads. It was concluded that the lower blends of biodiesel increased the brake thermal efficiency and reduced fuel consumption. The trends of NO_x emission for COME were the same as that of diesel at lower loads and slightly higher at full loads.

Nagaprasad et al. (2009) experimentally studied the performance of NCO and its blend with diesel using preheating in a single cylinder four stroke, naturally aspirated, water cooled, direct injection diesel engine at a speed of 1500 rpm with variable loads. They have observed that 25% of NCO mixed with 75% diesel is the best-suited blend for diesel engine without heating and any engine modification. Blends containing 50%, 25% and 0% diesel require preheating up to 70°C, 80°C and 95°C respectively.

Lin & Lin (2011) studied the spray characteristics of emulsified castor oil biodiesel on engine emissions and deposit formation. They used a constant volume bomb to analyse the spray characteristics under elevated temperature. They observed that without changing the engine structure, with 5-10% increased injection pressure, the 82.8% castor oil biodiesel, 15% water, 2% bioethanol and 0.2% composite surfactant Span-Tween was the optimum combination for the diesel engine use.

Review of the available literature on the use of neat castor oil (NCO) and castor oil methyl ester (COME) in a diesel engine indicates that only performance, fuel economy and emission data were reported, but lacks in combustion analysis such as combustion duration, ignition delay, heat release rate, mass rate of fuel burnt, and maximum rate of pressure rise. Hence, the present work focuses mainly on the combustion analysis of neat castor oil (NCO) and castor oil methyl ester (COME) along with emission and performance analysis.

It is very difficult to start and operate a diesel engine using neat castor oil because of extremely high viscosity. To improve the performance and emission characteristics of the engine running with NCO and to understand the effects of physical properties of the fuel on the engine performance and emissions, a detailed investigation is required on the underlying combustion and heat release characteristics. Experiments were carried out to obtain the performance, fuel economy, combustion and emission characteristics of a single cylinder diesel engine using diesel, NCO and COME at various loads at a constant speed of 1500 rpm. A comparative analysis of these parameters for diesel, NCO and COME fuels is presented; in particular detailed information on combustion characteristics is highlighted.

CASTOR OIL

Castor is cultivated in 30 different countries on a commercial scale, of which India, China and Brazil are the major castor growing countries accounting 90% of the world's production (Da Silva César et al. 2010). India is the leader in global castor production and dominates in international castor oil trade. India produces around 10 lakh tons of castor seed and around 5.5 lakh tons of castor oil every year. The Indian variety of castor has an oil content of 48% and 42% can be extracted, while the cake retains the rest. Castor grows under tropical conditions. A hot and humid climate is required for its production. Castor oil obtained from castor seed is non-edible, but is of some industrial importance. Castor seed harvested from the field is dried till the pods open. Seeds are hulled by using de-hullers or by hand to remove the seed from the pod.

Table 2: Properties of test fuels.

Properties	Standard Methods	Diesel	COME	NCO
Density@40°C(g/cc)	ASTM 1298	0.830	0.914	0.961
Kin. Viscosity@40°C (cSt)	ASTM D445	2.6	14.65	226.2
Gross Calorific Value (kJ/kg)	ASTM D240	42,500	36,605	34,696
Calculated Cetane Index	ASTM D976	47	40	28

Table 3: Engine specifications.

Make	Kirloskar
Model	TV1
Type of engine	4 stroke single cylinder, CI, Vertical, water cooled
Rated power	5.2 kW @ 1500 rpm
Compression ratio	17.5:1
Engine bore	87.5mm
Stroke	110mm
Cubic capacity	661.5cm^3
Loading device	Eddy current dynamometer

Extraction of oil from castor seed is done similar to that of most other oilseeds. The ripe seeds are allowed to dry after they split open and discharged. These seeds are cleaned, cooked and dried before extraction. Cooking is done to coagulate protein (necessary to permit efficient extraction), and to free the oil for efficient pressing. The first stage of oil extraction is done using a high-pressure continuous screw press mechanism, which is called as expeller. The extracted oil is filtered and the material removed from the oil is fed back into the stream along with fresh material. Material finally discharged from the press, called cake, contains 8 to 10% oil. It is crushed into a coarse meal and subjected to solvent extraction with hexane or heptane.

Castor oil is one of the very high viscous oils, where the oil content in the seed is relatively high. The oil itself contains a number of fatty acids such as oleic acid, linoleic acid, stearic acid and palmitic acid as given in Table 1. However, among various vegetable oils, castor oil is distinguished by its high content (over 85%) of ricinoleic acid.

Fig. 1 shows the experimental setup used for transesterification. Neat castor oil was converted into biodiesel through the alkaline transesterification reaction for which potassium hydroxide (KOH) was used as a catalyst with methanol. One percent of potassium hydroxide catalyst was dissolved in methanol by 50% by volume and mixture was added to the neat castor oil. Then the prepared mixture was stirred at 60°C for 30 minutes. After that, the reactant material was poured into a transparent vessel and allowed for cooling at room temperature for 8 hrs. It was allowed to settle for separation of glycerol as the bottom layer. The upper layer of biodiesel was put into another transparent vessel for washing with an equal amount of water. This biodiesel was heated up to 110°C for 10 minutes to remove excess water. Then the biodiesel was cooled down to room temperature before use.

EXPERIMENTAL SETUP AND TEST PROCEDURE

A single cylinder, 4-stroke, water-cooled, constant speed, compression ignition engine developing power output of 5.2 kW @ 1500 rpm was used for this experimental work. The engine specifications are given in Table 3. The engine cylinder was fitted with a piezoelectric transducer for sensing the cylinder pressure at every degree of crank angle. An optical shaft position was used to give a signal at TDC and an eddy current dynamometer was fitted to the engine to

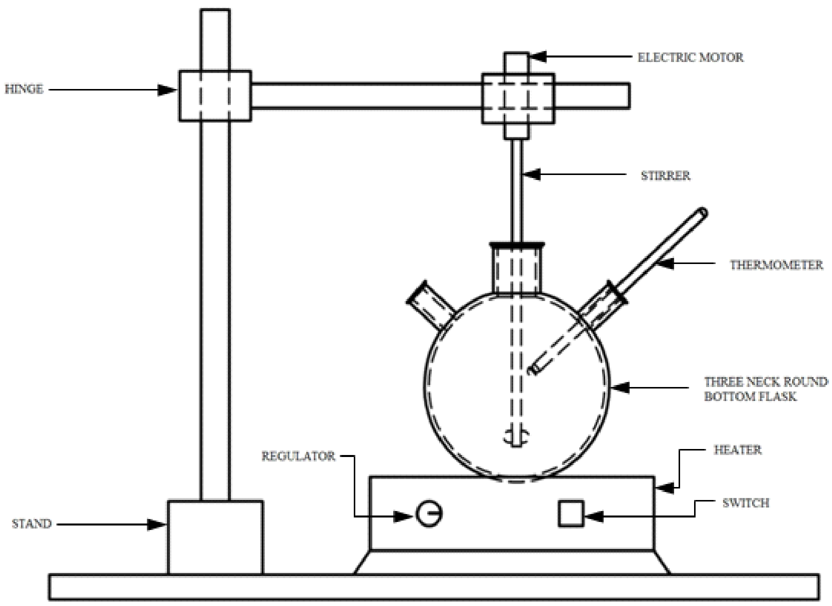

Fig. 1: Schematic diagram of esterification setup.

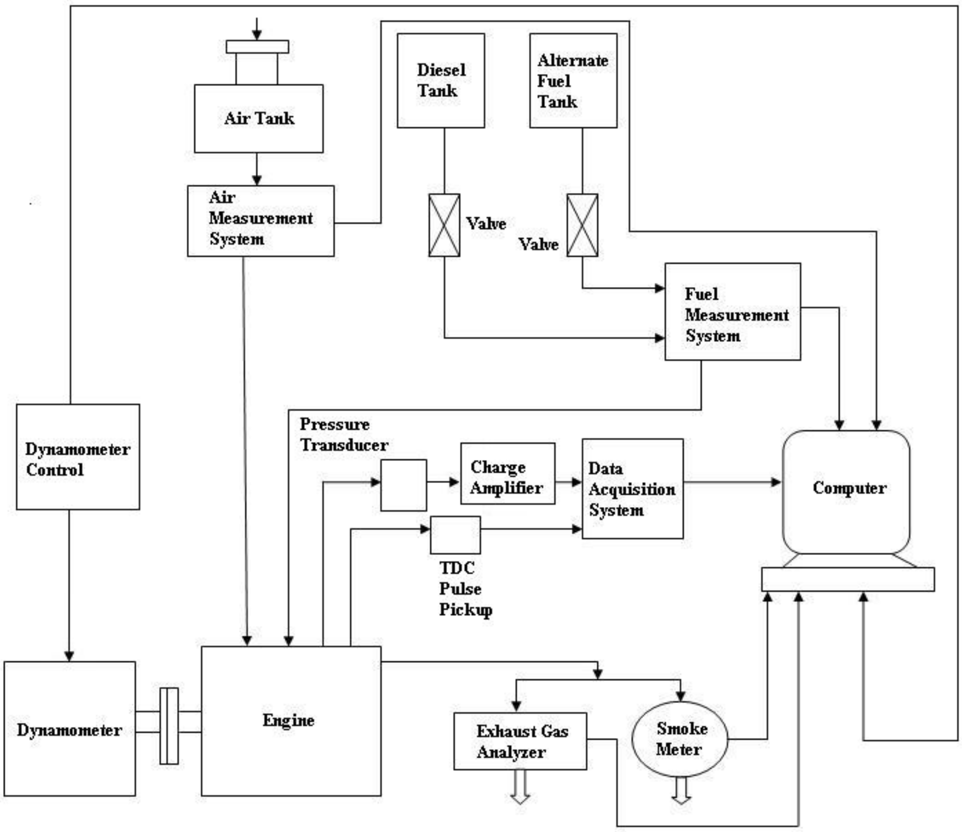

Fig. 2: Schematic diagram of experimental setup.

apply load and measure the power output of the engine at various loads. A high-speed data acquisition system was used to record the pressure crank angle data. The intake air and diesel consumption measurements were obtained from pressure transmitter interfaced instruments. The 'Engine Soft' software was interfaced with the engine with the help of suitable hardware so that the sensors and transducers provided the required input to the software for the calculation of performance parameters. Carbon monoxide, unburnt hydrocarbon and NO emissions were measured using AVL five gas analyser at various loads on the engine. The smoke emission was measured by AVL smoke meter. A schematic of the experimental setup is shown in Fig. 2.

EXPERIMENTS

In this research work, experiments were carried out stage by stage from no load to full load operation with diesel, COME and NCO. The engine was operated at a constant speed of 1500 rpm for all loads. Torque, engine speed, fuel flow time, HC, CO, NO and smoke emissions were recorded. Performance of the engine was evaluated in terms of brake thermal efficiency, brake power, brake specific energy consumption from the above parameters. Combustion parameters such as ignition delay, combustion duration, peak pressure and maximum rate of pressure rise have been calculated from the pressure-crank angle data.

Results and discussion are presented based the following test fuels: i. Diesel, ii. COME, iii. NCO. The properties of test fuels are tabulated with ASTM standards in Table 2.

RESULTS AND DISCUSSION

Combustion Characteristics

Cylinder pressure: Fig. 3 indicates the variation of cylinder pressure with respect to the crank angle at full load. It can be observed that more heat release takes place for diesel operation when compared to NCO and COME due to better combustion which results in higher peak pressure. In the case of NCO, less fuel-air mixture is prepared during ignition delay period, resulting in lower heat release, and hence lower peak pressure. Heat release is delayed and more heat is released during diffusion combustion phase which results

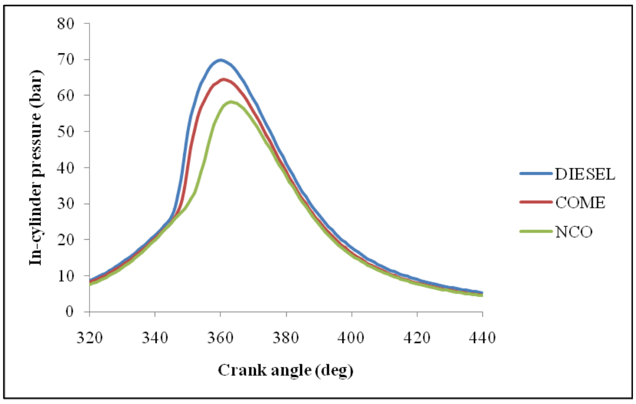

Fig. 3: Variation of cylinder pressure with degree crank angle at full load.

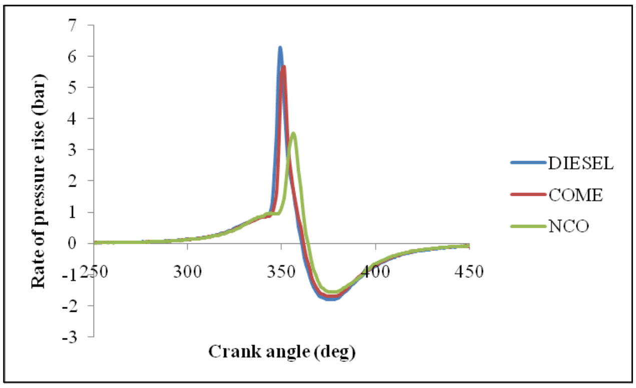

Fig. 4: Variation of rate of pressure rise with crank angle degree at full load.

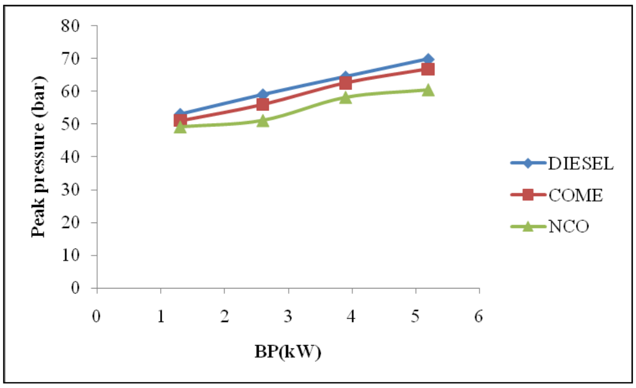

Fig. 5: Variation of peak pressure with brake power.

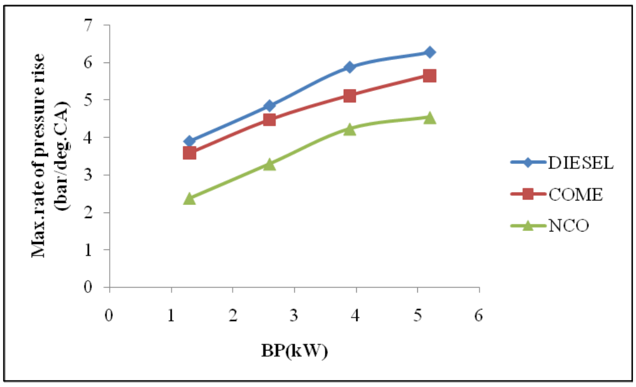

Fig. 6: Variation of maximum rate of pressure rise with brake power.

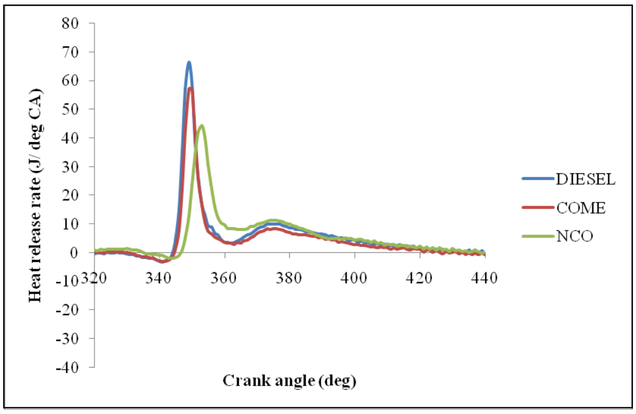

Fig. 7: Heat release rate diagram with respect to crank angle at full load.

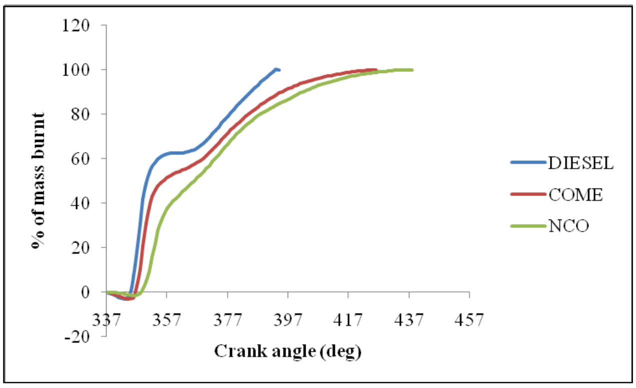

Fig. 8: Variation of percentage of fuel mass burnt with crank angle degree at maximum load.

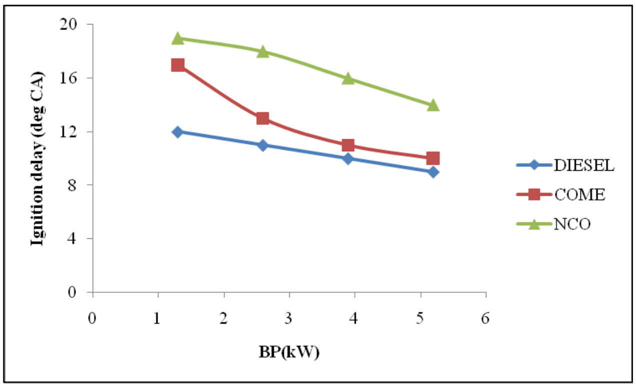

Fig. 9: Variation of ignition delay with brake power.

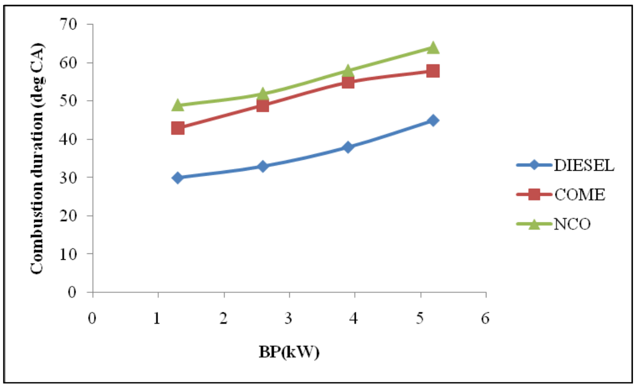

Fig. 10: Variation combustion duration with brake power.

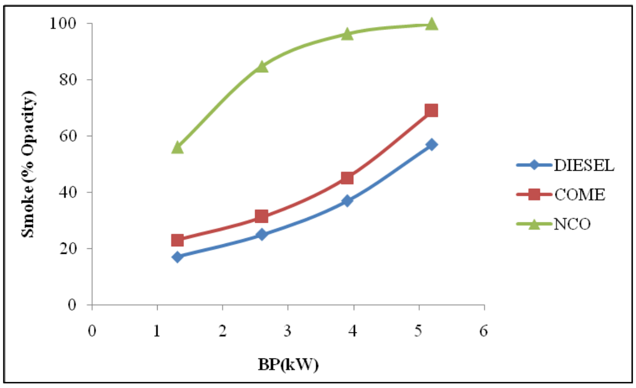

Fig. 11: Variation of smoke emission with brake power.

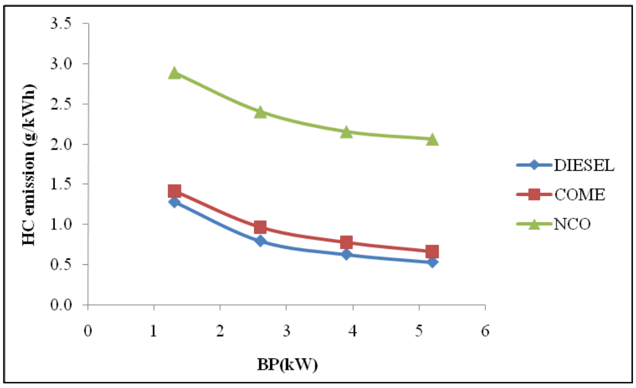

Fig. 12: Variation of HC emission with brake power.

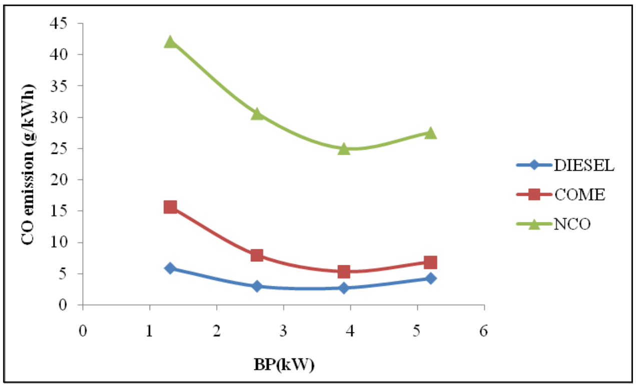

Fig. 13: Variation of CO emission with brake power.

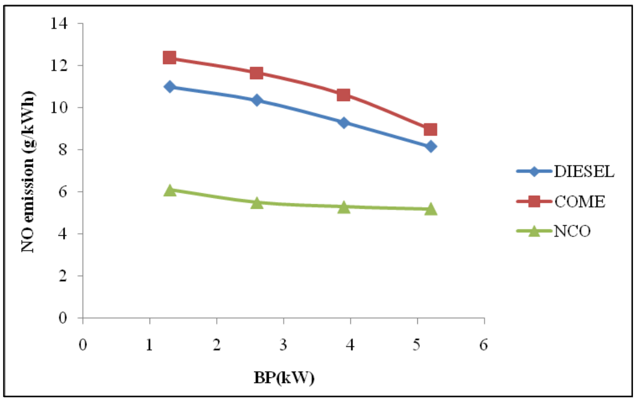

Fig. 14: Variation of NO emission with brake power.

in lower peak pressure, higher exhaust temperature and lowers useful energy conversion. With COME operation, combustion improves and hence higher heat release takes place, thereby cylinder peak pressure occurs closer to diesel operation.

Rate of pressure rise: Fig. 4 indicates the instantaneous rate of pressure rise after the combustion starts. The rate of pressure rise depends strongly on the initial combustion rate in diesel engines, which in turn depends on the amount of fuel taking part in the premixed combustion phase. Due to slow combustion rate of NCO, the instantaneous rate of pressure rise is lower for NCO. The rate of pressure rise increases to the level of diesel for COME as a result of improved fuel properties leading to better combustion.

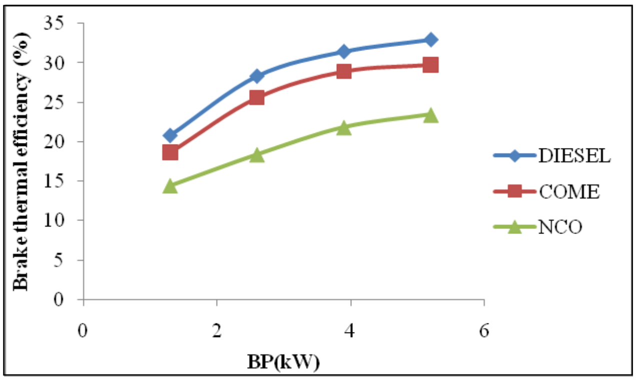

Fig. 15: Variation of brake thermal efficiency with brake power.

Cylinder peak pressure and maximum rate of pressure rise: Cylinder peak pressure and maximum rate of pressure rise for diesel, NCO and COME are shown in Fig. 5 and Fig. 6. The highest value of peak pressure and maximum rate of pressure rise is noticed with diesel. At full load, the peak pressure for diesel is 69.79 bar, whereas it is 60.49 bar for NCO. The combustion rate is lower for NCO as seen in Fig. 7. The peak pressure depends on the combustion rate during the initial period of premixed combustion phase which in turn depends on the amount fuel taking part in this period. During the pre-mixed phase, less amount of air-fuel mixture is prepared for combustion mainly because of the extremely high viscosity of NCO and hence the lower peak pressure. With castor oil biodiesel (COME), the peak pressure increases to 66.73 bar due to improved combustion. A similar trend is observed for the maximum rate of pressure rise. The maximum rate of pressure rise for diesel, COME and NCO is 6.27 bar/deg CA, 5.66 bar/deg CA and 4.54 bar/deg CA respectively.

Heat release rate: Heat release rate for diesel, COME and NCO at full load is shown in Fig. 7. The heat release rate may be divided into two parts: the premixed combustion and diffusion combustion. Particular interest with combustion studies has been with premixed combustion. It is seen that premixed combustion for diesel is associated with high rate of heat release rate compared to NCO and COME. Due to the high viscosity of NCO and subsequently with a reduction in fuel-air mixing rates, less fuel is being prepared for rapid combustion with NCO. Therefore, more burning takes place in the diffusion phase rather than in the premixed phase with NCO. The premixed heat release is the indication of brake thermal efficiency and NO emission. With a higher heat release rate correlating to higher NO emission, which can be realized from Fig. 15 and Fig. 14. Also, higher diffusion combustion is the indication of smoke emission which is evident from Fig. 11. The end of the premixed combustion has been defined as the dip after the premix spike leading to the diffusion combustion. Higher heat release rate in premixed combustion is observed with COME compared to NCO as a result of lower viscosity of the biodiesel. Higher heat release rate of COME in the premixed phase results in higher peak pressure and maximum rate of pressure rise with lower smoke level and higher NO emission.

Mass rate of fuel burnt: Fig. 8 represents the percentage mass of fuel burnt during the combustion period. The mass fraction burned was calculated by normalizing the cumulative gross heat release at each crank angle to the total heat released. It can be seen that rate of mass of fuel burnt is lower for NCO indicating slow combustion when compared to diesel. More fuel is burnt in the second phase of diffused combustion indicate late combustion and subsequently, the exhaust temperature is higher and brake thermal efficiency is lower when compared to diesel fuel. The combustion starts earlier with COME than NCO. Also, 100 % mass burned with COME is much earlier than NCO. These are the reasons for the increase in brake thermal efficiency and lower smoke emission with COME compared to NCO.

Ignition delay: Fig. 9 shows the variation of ignition delay with respect to brake power. The ignition delay is defined as the time duration between fuel injection and the start of combustion. The start of injection is usually taken as the time when the injector needle lifts off its seat (determine by a needle lift indicator). The start of combustion is more difficult to determine precisely. It is best identified from the change in slope of the heat release rate, determined from cylinder pressure data using the techniques. Ignition delay for NCO is longer for all loads when compared to diesel and COME because of very high viscosity, low volatility and high density of NCO. This contributes to poor atomization and fuel-air mixture preparation, thereby increasing the ignition delay. Ignition delay decreases with castor oil bio-diesel at all loads because of improved fuel properties such as lower viscosity and hence, shortening of the physical ignition delay. At full load, the ignition delay for NCO and COME is 14° CA, 10° CA respectively and 9° CA for diesel operation.

Combustion duration: The combustion duration is the time taken from 5% of heat release to 95% of heat release measured in terms of crank angle degree which is obtained from heat release analysis. Its variation with brake power for various fuels is shown in Fig. 10. Combustion duration is higher for NCO operation, indicating slow and sluggish combustion because of poor fuel spray formation characteristics as explained earlier. Diesel combustion is good which has combustion duration of 45° CA whereas the combustion duration of NCO is 64° CA which is reduced to 58° CA for COME. This improvement is attributed to better combustion and higher heat release rate of COME as a result of modified properties such as lower viscosity and density.

Emission Characteristics

Smoke emission: Fig. 11 shows the variation of smoke emission with respect to brake power for diesel, NCO, and COME. The viscosity of neat castor oil is very high compared to diesel. Hence, spray characteristics of NCO are very poor which leads to very sluggish combustion. Smoke opacity increases considerably for NCO, particularly at higher loads compared to diesel. The percentage of smoke opacity reaches a maximum of 100% opacity for NCO at full load. However, the engine emits less smoke of 69% opacity when operating with COME. There is a considerable reduction in viscosity and density for COME which results in improved combustion. The smoke level of the diesel engine is 57% opacity.

Hydrocarbon emission: Fig. 12 indicates the variation of HC emissions with respect to brake power for diesel, NCO and COME. NCO results in higher HC emissions compared to diesel. HC level varies from 2.89 g/kWh at 25% load to 2.07 g/kWh for NCO and with diesel operation, it is from 1.28 g/kWh at 25% load to 0.53 g/kWh at full load. Very high viscosity and density of NCO causes poor atomization and non-uniform mixing of air with bigger size fuel particles which leads to rich pockets that can result in higher HC emissions. COME operation improves the combustion as a result of lower viscosity and better atomization. The variation of HC emissions for COME is from 1.42 g/kWh at 25% load to 0.66 g/kWh at full load closer to diesel operation.

Carbon monoxide: Fig. 13 shows the variation of CO emission with respect to brake power for diesel, COME and NCO. Diesel engine operating on neat castor oil (NCO) emits very high CO emissions compared to diesel fuel operation, nearly six times higher than base diesel fuel. NCO operation emits 27.54 g/kWh compared to diesel emission value of 4.23 g/kWh at full load. This is mainly attributed to slow and incomplete combustion because poor volatility and viscosity of NCO which causes less atomization, vaporization and non-uniform air-fuel mixture preparation. However, CO emission considerably decreases with the engine operation of COME. This is mainly due to the improved spray characteristics, better vaporization and mixing of air-fuel mixture which leads to more or less complete combustion. CO emission is 27.54 g/kWh for NCO, decreases to 6.86 g/kWh for castor oil biodiesel (COME) which is closure to diesel operation.

Nitric oxide emission: Fig. 14 represents NO emission versus brake power for various loads at a speed of 1500 rpm for diesel, NCO and COME. Specific NO emission is very low for neat castor oil when compared to diesel operation. With NCO, combustion is very sluggish and incomplete due to the very high viscosity and density of the fuel. As a result, heat released during the premixed combustion phase is less which results in lower combustion temperature and hence lower NO emission. At full load, the specific NO emission for NCO is 5.21g/kWh, whereas it is 8.17g/kWh for diesel operation. With esterification process, fuel properties such as viscosity and density improve, resulting in better combustion than NCO. This fact along with oxygen availability in the fuel increases the heat release rate compared to NCO. Hence, specific NO emission of 8.99 g/kWh for COME is higher even when compared to diesel operation.

Performance Characteristics

Brake thermal efficiency: Fig. 15 shows the variation of brake thermal efficiency with respect to brake power for diesel, NCO and COME for various loads at a speed of 1500 rpm. Brake thermal efficiency is inferior with NCO compared to diesel. Even though the engine was able to run with NCO after sufficient warm up with diesel fuel for nearly 20 min at full load, the combustion is very poor with NCO. NCO has higher viscosity and density compared to diesel. This results in poor spray characteristics with large size fuel particles. Atomization, vaporization and mixing become improper leading to late and incomplete combustion. The properties of castor oil such as viscosity, density and calorific value improve after transesterification process. This leads to better atomization, vaporization and mixture formation before combustion takes place. Hence, combustion and subsequent heat release are good, contributing to higher brake thermal efficiency. The brake thermal efficiency for NCO at full load is 23.47%. This increased to 29.73% for COME, where it is 32.94% for diesel.

CONCLUSIONS

Based on the experimental investigations in a single cylinder four stroke compression ignition engine using neat castor oil (NCO), castor oil methyl ester (COME) and diesel, the following conclusions are drawn:

- Diesel engine could not be started and operated directly using castor oil which has a very high viscosity of 226.2 cSt. However, it was found that after running the engine for about 20 minutes with diesel fuel at full load and replacing the filter, the engine was successfully operated using neat castor oil. Subsequently, the necessary performance data was generated with NCO and compared with COME and diesel.

- Peak pressure and maximum rate of pressure rise are lower for NCO compared to diesel due to higher viscosity, poor fuel-air mixture formation which results in incomplete combustion. Combustion improves for COME and approaches to the diesel level.
- Heat release rate with NCO indicates higher diffusion burning and lower premixed burning rates as compared to diesel. This results in lower brake thermal efficiency and higher exhaust temperature and smoke emission. COME operation increases the premixed combustion phase which leads to increase in brake thermal efficiency.
- The mass rate of fuel burnt and instantaneous rate of pressure rise is lower for NCO when compared to diesel due to poor combustion. Improved combustion is noticed for COME as indicated by higher rate fuel burnt and a higher rate of pressure rise.
- Combustion duration for NCO is 64°CA which is very high compared to diesel value of 45°CA. This indicates very slow and sluggish combustion of NCO. Combustion duration is reduced to 58°CA for COME with enhanced combustion.
- Ignition delay for NCO is higher for all loads when compared to diesel and COME because of poor atomization and fuel-air mixture preparation, thereby increasing the ignition delay. Ignition delay decreases with biodiesel of castor oil at all loads because of improved fuel properties. At full load, the ignition delay for NCO, COME and diesel is 14°CA, 10°CA and 9°CA respectively.
- Use of NCO in a diesel engine results in inferior performance and higher emissions when compared to diesel because of very high viscosity, high density and low volatility which results in poor atomization and fuel-air mixing leading to very poor combustion which is evident from combustion characteristics.
- An HC and CO emission for NCO operation is very high at all loads when compared to diesel due to poor atomization and non uniform fuel-air mixing which results in incomplete combustion. Castor oil biodiesel operation improves the combustion and emits marginally higher HC and CO emissions compared to diesel operation.
- Specific NO emissions for NCO, COME is 5.21g/kWh, 8.99g/kWh respectively. With NCO, less heat is released during the premixed combustion phase due to poor preparation of fuel-air mixture. However, COME operation results in higher combustion temperature with improved combustion because of oxygen availability in the fuel structure. Hence, specific NO emissions for COME is even higher than diesel operation which has a value of 8.17 g/kWh.
- Smoke level with NCO is very high and it is 100% opacity at full load indicating very slow and incomplete combustion as a result of very high viscosity. With COME fuel spray characteristics, atomization, vaporization and fuel-air mixing improve, leading to better combustion. Smoke level reduces to 69% opacity whereas it is 57% for diesel operation.
- At full load, the brake thermal efficiency with NCO is 23.47%, whereas it is 32.94% for diesel operation. With esterified castor oil, the combustion improves with a lower viscosity of the fuel which results in better fuel spray characteristics and fuel-air mixing. Brake thermal efficiency of COME is 29.73% which approaches closer to diesel.

In summary, after an initial warm-up period of twenty minutes with diesel, the engine could be operated successfully with neat castor oil. However, the present research work using NCO indicates that the combustion behavior is deplorable compared to diesel. This is reflected in terms of higher ignition delay, longer combustion duration, lower heat release rate, etc. However, the combustion improves considerably after converting NCO into its biodiesel. The performance, fuel economy, emission and combustion characteristics are closer to diesel. Engine performance can be equalized to diesel level if a small quantity of diesel (about 10% to 20% by volume) with castor oil biodiesel is blended.

REFERENCES

Agarwal, A. K. and Dhar, A. 2010. Comparative performance, emission, and combustion characteristics of rice-bran oil and its biodiesel in a transportation diesel engine. Journal of Engineering for Gas Turbines and Power, 132(6): 064503.

Agarwal, D. and Agarwal, A. K. 2007. Performance and emissions characteristics of jatropha oil (preheated and blends) in a direct injection compression ignition engine. Applied Thermal Engineering, 27(13): 2314-2323.

Altun, Sehmus and Rodríguez-Fernández, J. 2016. Biofuels derived from Turkish industry wastes-a study of performance and emissions in a diesel engine. Environmental Progress & Sustainable Energy, 35(3): 847-852.

Bari, S., Lim, T. H. and Yu, C. W. 2002. Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. Renewable Energy, 27(3): 339-351.

Canakci, M., Ozsezen, A. N. and Turkcan, A. 2009. Combustion analysis of preheated crude sunflower oil in an IDI diesel engine. Biomass and Bioenergy, 33(5): 760-767.

Da Silva César, A. and Otávio Batalha, M. 2010. Biodiesel production from castor oil in Brazil: a difficult reality, Energy Policy, 38(8): 4031-4039.

Demirbas, A. and Fatih Demirbas, M. 2011. Importance of algae oil as a source of biodiesel. Energy Conversion and Management, 52(1): 163-170.

Dias, J. M., Araújo, J. M., Costa, J. F., Alvim-Ferraz, M. C. M. and Almeida, M. F. 2013. Biodiesel production from raw castor oil. Energy, 53: 58-66.

Dhananmurugan. A. and Subramanian. R. 2015. Emission and performance characterstics of a diesel engine operating diesel-bael (*Aegle marmelos*) biodiesel blends. Nature Environment and Pollution Technology, 14(2): 331-336.

Geo, V. Edwin, Nagarajan, G. and Nagalingam, B. 2008. Studies on dual fuel operation of rubber seed oil and its bio-diesel with hydrogen as the inducted fuel. International Journal of Hydrogen Energy, 33(21): 6357-6367.

Ghanei, Rouhollah 2015. Improving cold-flow properties of biodiesel through blending with nonedible castor oil methyl ester. Environmental Progress & Sustainable Energy, 34(3): 897-902.

Hürdogan, Ertaç 2016. Thermodynamic analysis of a diesel engine fueled with diesel and peanut biodiesel. Environmental Progress & Sustainable Energy, 35(3): 891-897.

Kumar, M.S. and Jaikumar, M. 2014. A comprehensive study on performance, emission and combustion behavior of a compression ignition engine fuelled with WCO (waste cooking oil) emulsion as fuel. Journal of the Energy Institute, 87(3): 263-271.

Kumar, M.S., Kerihuel, A., Bellettre, J. and Tazerout, M. 2005. Experimental investigations on the use of preheated animal fat as fuel in a compression ignition engine. Renewable Energy, 30(9): 1443-1456.

Lin, Y.S. and Lin, H.P. 2011. Spray characteristics of emulsified castor biodiesel on engine emissions and deposit formation. Renewable Energy, 36(12): 3507-3516.

Nabi, M. N., Rahman, M. M. and Akhter, M. S. 2009. Biodiesel from cottonseed oil and its effect on engine performance and exhaust emissions. Applied Thermal Engineering, 29(11-12): 2265-2270.

Nagaprasad, S., Vijayakumarreddy, K., Kumar, P.S.P., E. Ramjee, Heppel O.D. and Nivendgi, M.C. 2009. Performance and emission characteristics of a diesel engine with castor oil. Indian Journal of Science and Technology, 2(10): 25-31.

Panwar, N. L., Shrirame, H. Y., Rathore, N. S., Jindal, S. and Kurchania, A. K. 2010. Performance evaluation of a diesel engine fueled with methyl ester of castor seed oil. Applied Thermal Engineering, 30(2-3): 245-249.

Panwar, N. L. and Shrirame, H. Y. 2009. The emission characteristics of a compression ignition engine operating on castor oil methyl ester. International Journal of Global Warming, 1(1/2/3): 368.

Scholz, V. and da Silva, J. N. 2008. Prospects and risks of the use of castor oil as a fuel. Biomass and Bioenergy, 32(2): 95-100.

Singh, P.J., Khurma, J. and Singh, A. 2010. Preparation, characterisation, engine performance and emission characteristics of coconut oil based hybrid fuels. Renewable Energy, 35(9): 2065-2070.

Sureshkumar, K., Velraj, R. and Ganesan, R. 2008. Performance and exhaust emission characteristics of a CI engine fueled with Pongamia pinnata methyl ester (PPME) and its blends with diesel. Renewable Energy, 33(10): 2294-2302.

Thiyagarajan, S., Geo, V.E., Martin, L.J. and Nagalingam, B. 2016. Effects of low carbon biofuel blends with Karanja (*Pongamia pinnata*) oil methyl ester in a single cylinder CI engine on CO_2 emission and other performance and emission characteristics. Nature Environment and Pollution Technology, 15(4): 1249-1256.

Valente, O. S., da Silva, M. J., Pasa, V. M. D., Belchior, C. R. P. and Sodré, J. R. 2010. Fuel consumption and emissions from a diesel power generator fuelled with castor oil and soybean biodiesel. Fuel, 89(12): 3637-3642.

Wander, P. R., Altafini, C. R., Colombo, A. L. and Perera, S. C. 2011. Durability studies of mono-cylinder compression ignition engines operating with diesel, soy and castor oil methyl esters. Energy, 36(6): 3917-3923.