Journal of Thermal Analysis and Calorimetry (2019) 137:593–605
https://doi.org/10.1007/s10973-018-7948-6

Effects of thermal barrier coating on the performance, combustion and emission of DI diesel engine powered by biofuel oil–water emulsion

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Received: 10 July 2018 / Accepted: 23 November 2018 / Published online: 3 December 2018

Abstract

Owing to the fast depletion of fossil fuels and their skyrocketing price due to the tremendous demand, they become imperative to find renewable alternative fuels for diesel engines. Vegetable oils and their mix with diesel in various proportions, called biodiesel, have been found to be very useful in reducing the alarming consumption of fossil fuels. In the present investigation, lemongrass oil is used as an alternative fuel. The availability of lemongrass oil is adequate for Tamil Nadu and Kerala. The coating material chosen is the partially stabilized zirconium because it has low thermal conductivity and high thermal coefficient. The piston top face, cylinder head, inlet valve and the outlet valve are coated. The purpose of low heat rejection engine or coated engine during the combustion process less heat is rejected by insulating materials. In the current work, the experiment is carried out with lemongrass oil with water emulsion and diesel in a four-stroke direct ignition engine with coating and without coating at various load conditions. The diesel engine run with lemongrass oil–water emulsion (94% LGO + 5% water + 1% surfactant), and low heat rejection engine performed better and gave better brake thermal efficiency compared with raw lemongrass oil–water emulsion blend at peak load. Then, the brake-specific fuel consumption of lemongrass oil–water emulsion in the coated engine was 325 (g kW^{-1} h^{-1}) which was lower than that of lemongrass oil–water emulsion (94% LGO + 5% water + 1% surfactant) in the uncoated engine. Further, combustion parameter of lemongrass oil–water emulsion blend tested in coated engine produced 60 bars in-cylinder pressure, and it was better than lemongrass oil–water emulsion in the uncoated engine. Both the cumulative heat release rate and the heat release rate were in superior range compared with lemongrass oil–water emulsion in the uncoated engine. As regards tailpipe emission, the lemongrass oil–water emulsion blend in the coated engine at peak load delivered a steep reduction in carbon monoxide, hydrocarbon and smoke emission of base diesel blend in the uncoated engine. But, on the contrary, NO_x and CO_2 emissions were steeply higher compared with the diesel blend that powered the uncoated engine. The entire tested parameters led to the conclusion that lemongrass oil–water emulsion used in the coated diesel engine would be a healthier and economical substitute fuel for hydrocarbonated fuels.

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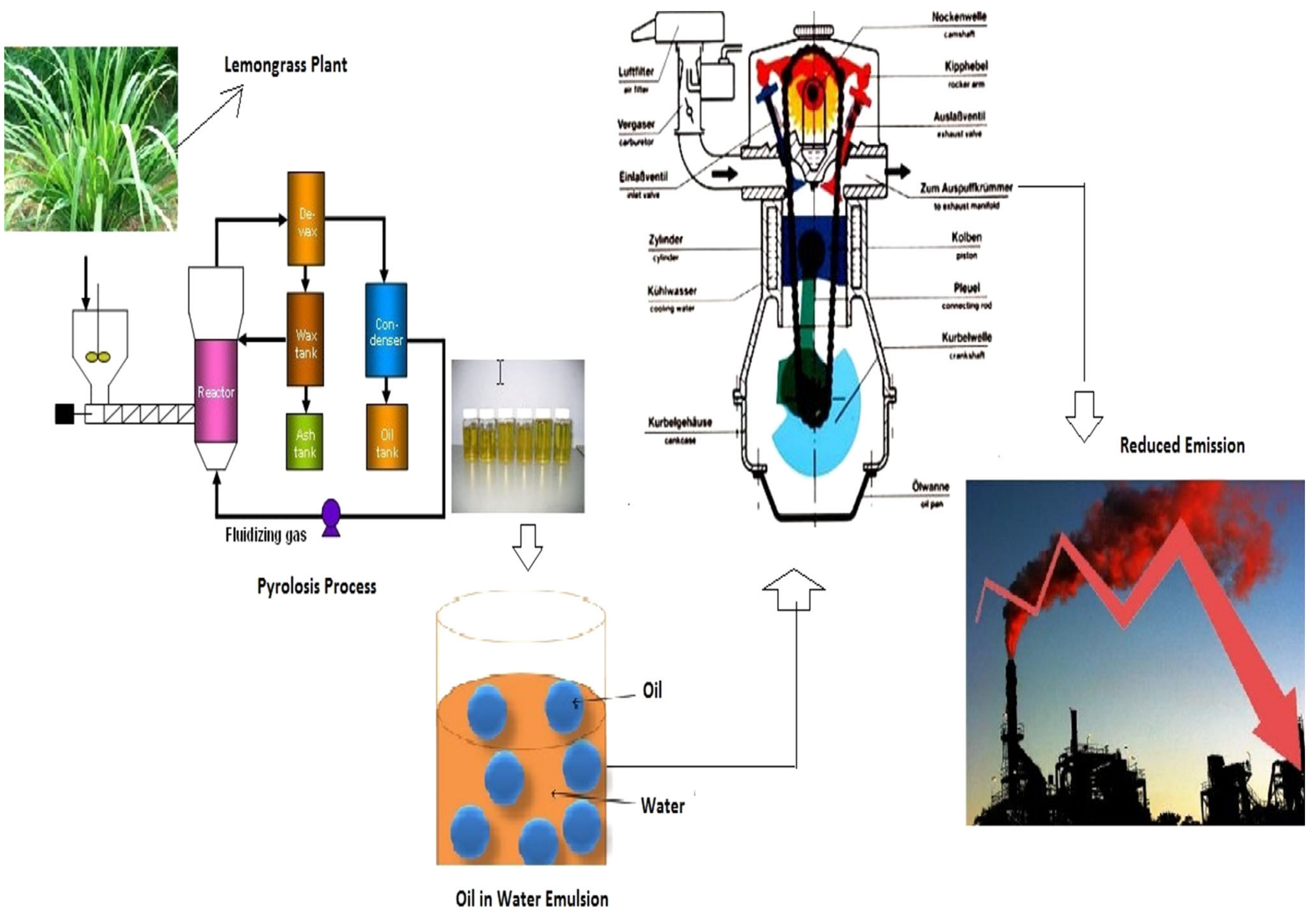
Graphical abstract



Keywords Lemongrass oil · Low heat rejection engine · Combustion · Emission

Abbreviations

LGWE UE (94% LGO + 5% water + 0.5% Span, 0.5% Tween) for uncoated engine
LGWE CE (94% LGO + 5% water + 0.5% Span, 0.5% Tween) for coated engine
LGO Lemongrass oil
LHR Low heat rejection engine
CE Coated engine
CI Compression ignition
CO Carbon monoxide
HC Hydrocarbon
NO_x Oxides of nitrogen
BTE Brake thermal efficiency
BSFE Brake-specific fuel energy
ID Ignition delay
CA Crank angle

Introduction

The search for an alternative source of energy has been going on for a long time now to find a feasible solution to the issues of fast reducing natural sources of oils and reducing environmental pollution being caused by emission of harmful gases such as CO and NO_x from the countless automobiles that are powered by petrol or diesel. Of the many alternative fuels that have been found to be effective and useful, the vegetable oils are used successfully as an alternative fuel in diesel engine. But they cannot be directly used in the engine because of their high viscosity and density. However, using the transesterification process the vegetable oil can be converted into biodiesel

[1]. Biodiesel is now utilized as an alternative fuel in the diesel engine as it has been found to be eco-friendly and it can be effortlessly removed from inexhaustible assets. It is one of the best alternative fuels, and it can be extracted from the plant seed oil [6]. Since 1990, numerous specialists have taken up the investigation on the use of alternative fuels to deal with environmental crisis and energy. Oil yield is the essential source for biofuel production [2]. Biofuel is a contrasting option to regular oil-based fuels that can be obtained from different sources such as vegetable oil, creature fats and squander oil. Besides, it has a great deal of favourable position due to its biodegradable, non-poisonous and sulphurless property. Moreover, in different nations, a noteworthy consideration has been paid in the change in the substitution of vital sources. The offer of bio-energies in the car business is assessed to increase quickly [3].

Nowadays, many researches focus on the field of low viscous oil (biofuel) as it has low viscosity, low density, low advantage, non-toxicity, eco-friendly and biodegradation [4]. The fuel properties of diesel are very close to those of low viscous oil. *Cymbopogon flexuosus* (lemongrass oil) was the biofuel used in the diesel engine. The C20 + D80 results came close to diesel value. The brake thermal efficiency increased in C20 + D80 compared with neat diesel emission parameters such as hydrocarbon and carbon monoxide, where smoke decreased as compared to diesel. Compared with neat diesel fuel, there is an increase in carbon dioxide (CO_2) and oxides of nitrogen (NO_X) [7].

In the pyrolysis method, the waste fish fat was collected from the nearness of impetus to prepare biofuel for diesel engines. The increase in engine thermal efficiency (BTE) of pure biofuel showed the result of 32.4% at 80% of load condition compared with diesel (29.98%). The oxides of nitrogen were higher in pure biofuel at all load conditions. There is a decrease in the hydrocarbon and carbon monoxide in neat biofuel compared with diesel [8].

The n-butanol was used as a biofuel in diesel engine with high compression ratio. The compression ignition (CI) of the premixed n-butanol and air blend was equipped for delivering diesel-like engine efficiency, higher oxide of nitrogen and smoke emission reduction. While increasing the engine load condition, n-butanol was consumed quickly and a sudden pressure increased [9].

In diesel engine, 20% of *Cymbopogon flexuosus* and 80% of pure diesel were used. The emission parameters including 12.28% smoke, 17% hydrocarbon and 43.66% carbon monoxide were reduced compared with neat diesel. At all load conditions, the oxides of nitrogen increased compared with the base diesel fuel [10].

Emulsification is a process of mixing two immiscible liquids, that is, water and oil, with the help of a surfactant. The two emulsion fuels E10 and E20 were prepared with the help of Span 80 surfactant. The brake thermal efficiency slightly decreased in emulsified fuel compared with neat diesel. The emission characteristics of oxide of nitrogen 51% and particulate matter 14% decreased when using emulsified fuel in the diesel engine [11]. In the investigation, the waste plastic oil was used in diesel engine. With the help of surfactant Span 80, 10%, 20% and 30% water content was added to the waste plastic oil. At full load condition, the 30% water content showed the reduction in the oxides of nitrogen 247 ppm and smoke 41%. The engine thermal efficiency was slightly increased using 10% water content in the fuels [12]. In the emulsion fuel, the waste cooking oil is used in diesel engine. Usage of the neat waste cooking oil resulted in increased hydrocarbon, smoke and carbon monoxide compared with diesel. The waste cooking oil emulsion showed the decrease in smoke and oxides of nitrogen (NO_X). Ignition delay and in-cylinder pressure of the neat waste cooking oil were higher in emulsion compared with waste cooking oil [13].

Many researchers have found that the low heat rejection engine improves the brake thermal efficiency and emission parameters at high temperature elevation during the combustion process. The low heat rejection engine's main purpose is to have more heat dissipation in the combustion chamber to increase the engine's thermal efficiency characteristics, increase the emission parameters such as smoke and oxides of nitrogen and increase the fuel economy without any modification of engine components [14]. In this examination, the piston top surface was coated with YSZ materials by using the plasma spray techniques; the coating thickness deposited was 250 microns, and it showed an increase in thermal efficiency, oxides of nitrogen and oxygen. Emission characteristics such as carbon monoxide and hydrocarbon were slightly decreased, and the combustion characteristics such as cylinder pressure and heat release rate were in low in heat rejection engine [15] while reducing the heat losses in low heat rejection engine or adiabatic engine in the year 1960. Increasing the engine coolant temperature at different load conditions operating at a speed range of 1500 rpm was investigated. When comparing analytical and experimental values, it showed that there is an increase in the effect of engine coolant temperature on efficiency of fuel conversion [16]. The partially stabilized zirconium coating material having the thickness of 450 microns was used for this investigation. It was found that the coated engine had increased engine thermal efficiency of 6% when compared with uncoated diesel engine. The emission parameters such as smoke, hydrocarbon and carbon monoxide were reduced to 14.3%, 7.2% and 27.52%, respectively, at full load condition. The oxides of nitrogen and brake thermal efficiency increased in low heat rejection engine [17].

From the detailed literature survey, it was found that there is a huge vacuum with the usage of low viscous biofuel in the diesel engine with a fuel modification strategy of emulsification technique and the engine modification strategy of low heat rejection coating on the piston crown. Hence, in the present research work, the low viscous biofuel lemongrass oil is used, which is taken as 94% raw biofuel, 5% water and 1% surfactant. At the outset, the diesel engine piston is coated and its performance, combustion and emission characteristics are compared with those of coated and uncoated piston. Then, the coated piston is compared with the engine using lemongrass oil–water emulsion.

Table 1 The properties of diesel and lemongrass oil–water emulsion

Fuel properties	Diesel	LGWM1
Density/kg m^{-3} @ 25 °C	832	841
Calorific value/MJ kg^{-1}	44.2	41.51
Kinematic viscosity (cSt) @ 40 °C	2.8	2.7
Cetane number	48	46
Flash point/°C	57	69
Fire point/°C	65	83
Acid number/mg KOH/g	0.01	0.03
Cloud point/°C	−15 to 6	–3 to 13
Latent heat of vapourization/kJ kg^{-1}	252	421
Heating value	42,800	32,435

Materials and methods

Outline of *Cymbopogon flexuosus* (lemongrass oil)

Cymbopogon flexuosus biofuel is prominent amongst the most imperative fundamental oils delivered in India. It is very well known and is produced in large quantities in Kerala [3]. At the same time, it is more disorganized and extracted on a splinter scale. Considering the financial aspects of lemongrass oil, the production is so tedious. This section endeavours to shed light on this viewpoint of production, i.e. profitability, cost and feasibility of lemongrass oil preparation. The lemongrass oil biofuel is extracted using a steam distillation process, and the lemongrass oil belongs to the group of Poaceae and is chemically formulated as $C_{51}H_{84}O_5$ [10]. *Cymbopogon flexuosus* biofuel consists of citral 65% and 12% geranyl acetate and some amount of other aromatic compounds. Its molecular weight is 777.2, and it consists of 80% of hydrogen, 10% of oxygen and 10% of carbon [7].

Emulsification process

Emulsification is a process of two immiscible fluids mixing with the help of surfactant. The surfactant helps the emulsion to be well balanced regardless of whether it is made of scattered water and a persistent oil stage [13]. The Span and Tween are very important in the emulsification process because they depend upon the stability of emulsion [18]. Specified amounts of lemongrass oil and water are taken in a glass container. Surfactant (Span 80 and Tween 80) is added into the container and continuously stirred at a particular rpm speed to achieve better mixing of product to form the emulsion. The lemongrass oil–water emulsion is directly used in the engine without any alternation because it has the viscosity and the density very close to those of the base diesel [19]. Table 1 shows fuel properties and composition of lemongrass oil–water emulsion, the calorific value and cetane number which is very close to that of the base diesel fuel.

Micro emulsion

Micro emulsion is the process of eventually breaking up high quantity of droplets of fuels into small quantity of droplets of fuels. The size of the fuel droplets is measured in microns. When the emulsified fuel is to be injected through the combustion chamber, it can be disclosed to high combustion temperature. In the first stage, the water droplets are exposed to the fuel, in the second stage, the water droplets are exploded due to the boiling point temperature of water being lower than that of diesel, and in the third stage, the emulsified fuel is finally atomized. Figure 1 illustrates the concept of microexplosion.

Coating materials

The coating material partially stabilized zirconium is used in the diesel engine. The piston top face inlet valve and the outlet valve are coated using plasma spray technique. The coating material's thickness preferred is 500 µm because it has low thermal conductivity and higher thermal coefficient when compared with the other ceramic materials. Also, there is a prerequisite for a high melting point, remarkably higher than 2000 °C and additionally phase strength up to 1400 °C or surprisingly better up to the melting point. The coating thickness is taken as 500 microns because it is more efficient and can give 10% improvement in BTE on an average with the penalty of 15% increase in NOx based on the earlier study [17]. Figure 2 shows the photograph of the coated surface of piston valve facing.

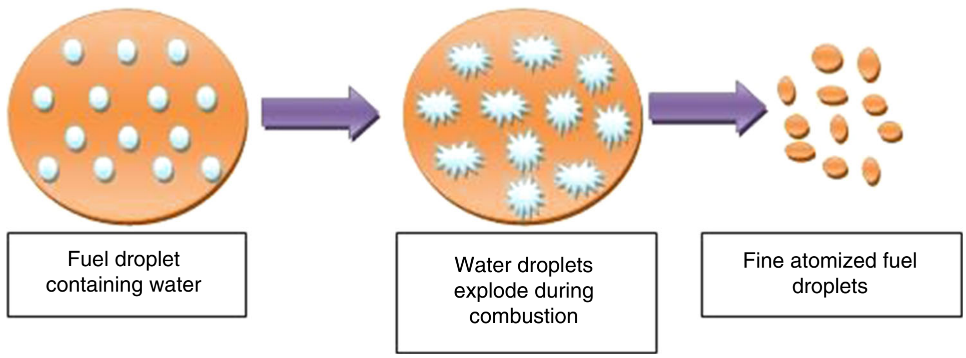


Fig. 1 Concept of microexplosion

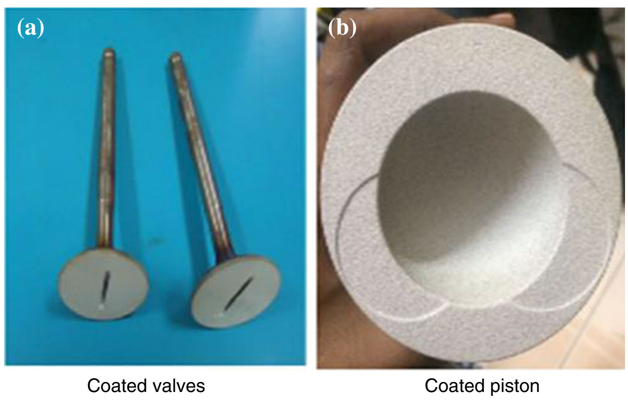


Fig. 2 Photograph of coated surface of piston, valve facing

Experimental set-up and uncertainty analysis

The four-stroke single-cylinder direct ignition diesel engine is shown in Fig. 3. The engine specifications are also given in Table 2. An experimental work was carried out in a Kirloskar SV1 vertical water-cooled engine delivering a power of 5.1 kW at 1500 rpm. The eddy current was coupled with the test engine with a compression ratio of 17:5:1 and displacement of 661 cm^3. Two independent tanks were used for base diesel fuel and lemongrass oil–water emulsion by using different operating load conditions of 25%, 50%, 75% and 100% and using the tested fuel of LGWE (94% LGO + 5% water + 1% surfactant) and pure diesel compared with coated and uncoated direct ignition engine. The HC, CO and NO_x emissions were estimated with the assistance of AVL-444 five gas analyser, and smoke emission was estimated with the assistance of Bosch smoke meter [5]. The top dead centre encoder and data acquisition chord systems with the assistance of computer were used to measure the combustion parameters [20]. The instruments used were from different manufacturers, so for proving the accuracy uncertainty analysis is required. Errors due to the working condition, environmental, observation and calibration were corrected using uncertainty analysis. Average values were noted by conducting each experiment five times to obtain accuracy in results. The tabulation consists of values of errors and measured quantity of experiments including the experimental errors that occurred during analytical methods [45]. The uncertainties of the quantity parameters are given in Table 3.

Results and discussion

The performance, combustion and emission characteristics of uncoated diesel engine fuelled with LGWE (94% LGO + 5% water + 1% surfactant) and pure diesel are compared with those of low heat rejection engine. The low heat rejection engine is otherwise called coated engine.

Performance characteristics

Brake thermal efficiency (BTE)

The brake thermal efficiency of an engine is an imperative parameter that would show the effectiveness of the engine and may be determined as the incorporation of mechanical efficiency and net indicated thermal efficiency. Figure 4 shows the variation of BTE with esteem to brake power of diesel fuel and lemongrass water emulsion in compression ignition engine (CI) and low heat rejection engine (LHR). The BTE in a wide spectrum was characterized by the oxygen content, calorific value, cetane index and kinematic viscosity. The results shown in the plot reveal that mineral diesel fuel in both CI engine and LHR engine had higher values than the remaining combination of fuel that is LGWE in compression ignition and LHR engine. It is inferred that the LGWE shows higher thermal efficiency in LHR engine than in a compression ignition engine, and there were lower energy content of LGWE in diesel engine and higher efficiency in LHR due to the higher air–fuel

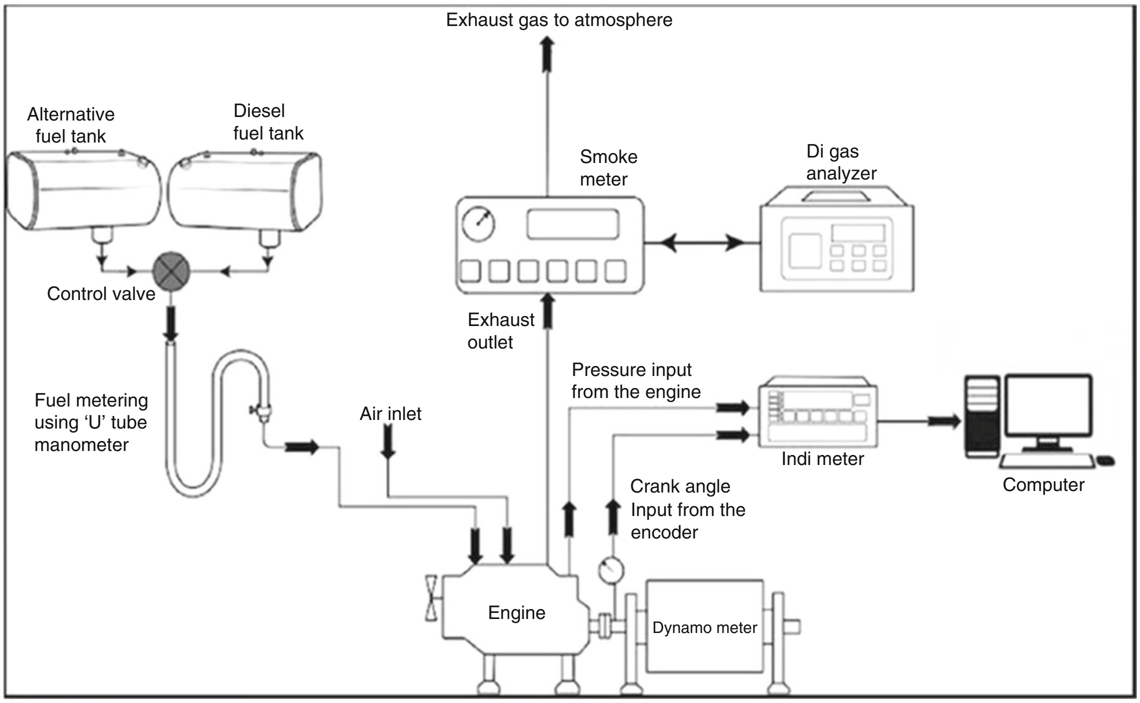


Fig. 3 Schematic diagram of experimental layout

Table 2 Test engine for specification

Engine details	Kirloskar, four-stroke single-cylinder diesel engine
Speed	1500 rpm
Power/kW	5.1
Bore/mm	87.5
Stroke/mm	110
Compression ratio	17.5:1
Injection timing	23° bTDC
Injection pressure	200 bars
Types	Water cooled

Table 3 Percentage of uncertainty

Parameter per cent uncertainty	%
BP	0.5
BSEC	0.8
BTE	1.01
CO	0.28
HC	0.9
NO_x	0.3
Smoke	0.6

interface. The atomization process in an LHR engine is more vigorous in diesel engine which in turn increases the BTE in LHR engine, which is due to the increased combustion temperature in LHR engine. The overall BTE is inferred through maximum load condition, thus resulting in diesel as fuel in LHR engine giving the highest value of 32% of BTE and 29% of BTE in CI engine. The value of BTE efficiency at maximum load condition for LGWE was found to be 28% in LHR engine, and this was followed by the lowest value of 27.5% for LGWE in diesel engine.

Brake-specific fuel consumption (BSFC)

The brake-specific fuel consumption of an engine is defined as the quantity of fuel consumed by an engine delivering one kilowatt power for 1 h. Figure 5 represents the comparison of BSFC with CI engine and LHR engine powered with diesel and LGWE. The plot represents the variations of BSFC of diesel and LGWE. The operating parameters such as load, injection, pressure, timing, nozzle diameter and speed also have their effects on BSFC. The results shown in the plot reveal that mineral diesel fuel in both CI engine and LHR engine had lower values than the remaining combination of fuel that is LGWE in compression ignition and LHR engine. It is inferred that the LGWE shows lower fuel consumption on LHR engine than a compression ignition engine. There are lower energy content of LGWE in diesel engine and minimal fuel consumption in LHR due to the higher air–fuel interface. The

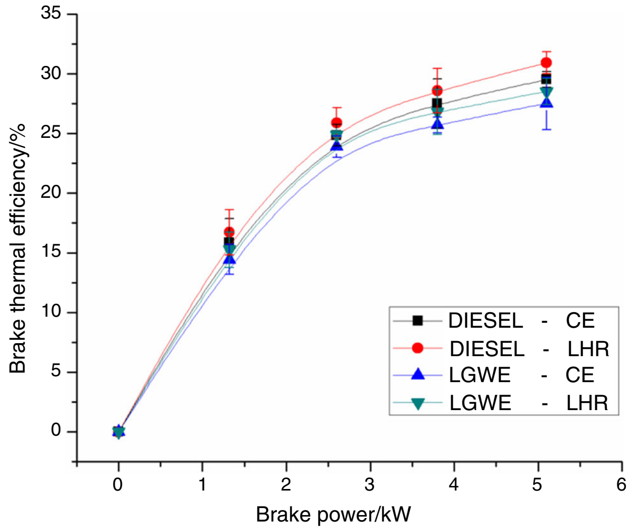


Fig. 4 Variation of lemongrass oil–water emulsion and its blend on BTE

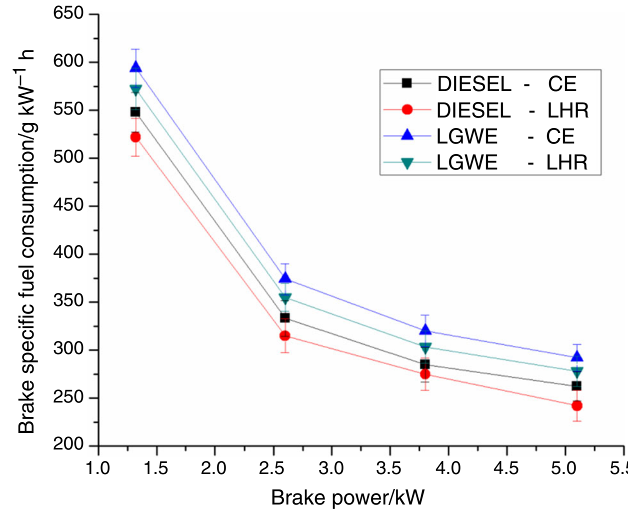


Fig. 5 Variation of lemongrass oil–water emulsion and its blend on BSFC

atomization process in an LHR engine is high in diesel engine which in turns decreases the BSFC in LHR engine. The increase in atomization is due to the increased combustion temperature in LHR engine. The overall BSFC is inferred through maximum load condition, and thus, results were observed for diesel fuel in LHR engine with a lowest value of 246.5 g kW^{-1} h^{-1}; then, diesel fuel with CI engine gives a BSFC value of 265 g kW^{-1} h^{-1}. The BSFC values for LGWE in LHR engine are 325 g kW^{-1} h^{-1}, and when LGWE is used as fuel for CI engine, it gives a BSFC value of 340 g kW^{-1} h^{-1} at maximum load condition.

Combustion characteristics

In-cylinder pressure

The compression process in a CI engine leads to the high cylinder pressure, and it is mainly a variable that is associated with the rate of burning test fuel in the preparatory phase of combustion, thus leading to peak pressure. The combustion characteristics mainly depend upon the cylinder pressure and also involve the load carrying capacity of an engine. The management of cylinder pressure varies some parameters such as counting cetane index, viscosity and air–fuel ratio, increasing ignition delay and larger fuel stagnation in the preparatory phase of combustion, faster rate of combustion and increased peak pressure. Figure 6 shows the variation plot of cylinder pressure (bar) and crank angle (°) at variable load values. The study explores the values of cylinder pressure of LGWE and diesel in CI engine and LHR engine. The trend reveals that the value of cylinder pressure of diesel in LHR engine is high, which is followed by diesel in CI engine, and the values of cylinder pressure are low for LGWE in LHR and also low for LGWE in CI engine. The values are lower for LGWE in CI engine, which is due to its lower atomization rate and poor evaporation rate. When compared with diesel, the cylinder pressure values of LGWE are lower because of its poor evaporation rate which in turn, perhaps, leads to low fuel air mixing. When compared with diesel, the cylinder pressure value of the LGWE is lower because of its higher cetane number, and also, this leads to lesser fuel stagnation which escalates the issue to lower ignition delay. The value of cylinder pressure for diesel in LHR engines was 65 bar, and for diesel in CI engine, it was 63 bar. The cylinder pressure value of LGWE in LHR engine was 60 bar, and that of LGWE in CI engine was 58 bar at maximum load condition. The lemongrass oil–water emulsion affected combustion process owing to available water content in the emulsified fuel reducing the cetane number of the test fuel, and relatively, the ID of the fuel also increased [21].

Heat release rate (HRR)

Figure 7 shows the plot of HRR (kJ m^{-3} deg^{-1}) versus crank angle (°) for the natural diesel and LGWE in CI engine and LHR engine, respectively. The values of LHR engine with diesel and LGWE show higher values of HRR when compared with CI engine with diesel and LGWE as fuel. This may be due to the lower calorific value of the LGWE added with its lower atomization rate and poor evaporation rate, besides poor air–fuel mixture rate. The higher cetane number of the LGWE also leads to lower HRR when compared with natural diesel. The highest peak values of HRR in LHR and CI engine for diesel were obtained as 74 kJ m^{-3} deg^{-1} and 71 kJ m^{-3} deg^{-1},

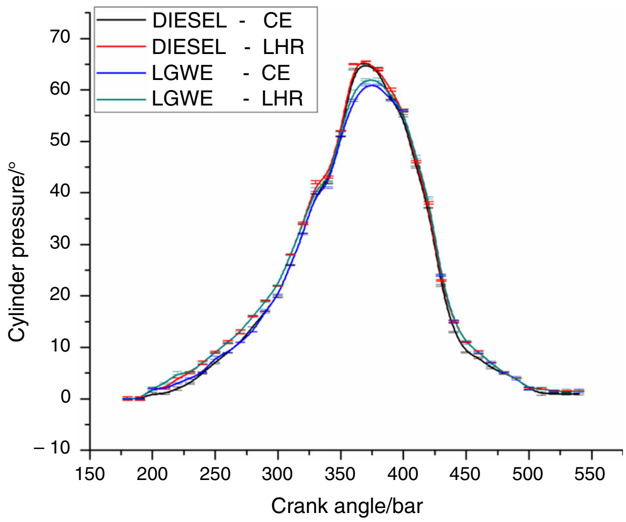


Fig. 6 Variation of lemongrass oil–water emulsion and its blend on cylinder pressure

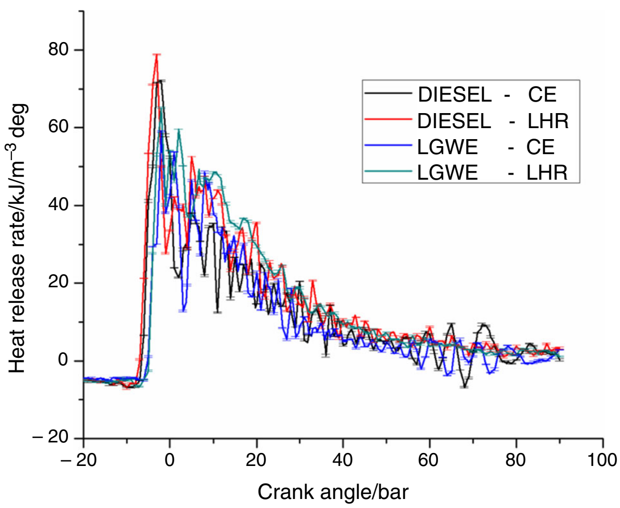


Fig. 7 Variation of lemongrass oil–water emulsion and its blend on HRR

respectively. The peak values of HRR were attained for LGWE in LHR and CI engine as 58 kJ m^{-3} deg^{-1} and 51 kJ m^{-3} deg^{-1}, respectively. It could be due to the superior combustion of lemongrass oil–water emulsion in the combustion chamber with a slightly increased temperature at thermal barrier coating [20].

Cumulative heat release rate (CHRR)

Figure 8 shows the values of cumulative heat release rate (CHRR) of diesel and LGWE in LHR engine. The LHR engine with diesel and LGWE shows higher values of HRR when compared with CI engine with diesel and LGWE as fuel. This may be due to the lower calorific value of the LGWE added with its lower atomization rate and poor

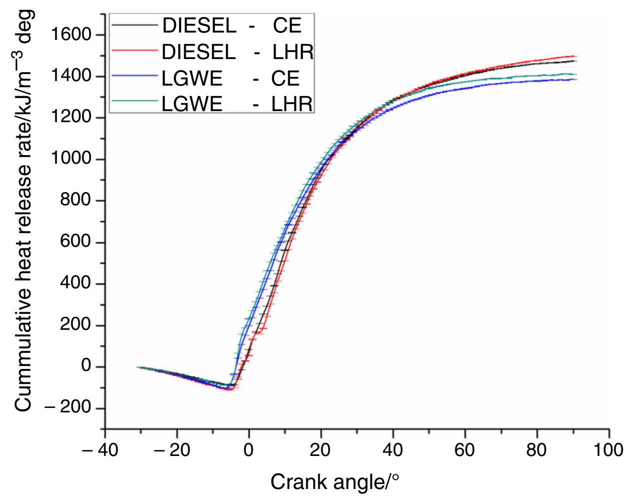


Fig. 8 Variation of lemongrass oil–water emulsion and its blend on CHRR

evaporation rate besides poor air–fuel mixture rate. The higher cetane number of the LGWE also leads to the property of lower HRR when compared with natural diesel. The highest peak values of CHRR in LHR and CI engine for diesel were 1500 kJ m^{-3} deg^{-1} and 1450 kJ m^{-3} deg^{-1}, respectively. The lowest peak value of CHRR was achieved with LGWE in LHR and CI engine of 1370 kJ m^{-3} deg^{-1} and 1360 kJ m^{-3} deg^{-1}, respectively.

Emission characteristics

Hydrocarbon (HC)

The plot illustrates the hydrocarbon (HC) emission of diesel and LGWE when used in a CI engine and an LHR engine as shown in Fig. 9 for multiple loading conditions. The emission level of hydrocarbon is higher for CI engine and LHR engine when diesel is used as fuel. When LGWE is used to energize the CI and LHR engines, it gives reduced emission values of HC. The reduced values of hydrocarbon emission may be due to the presence of oxygen which in turn intensifies the combustion rate, thus enabling lesser emission of HC. In CI engine powered with diesel, the absence of oxygen induces reduced combustion rate. The engine may also emit more hydrocarbon emission this may be attribute to under mixing, over mixing, wall impingement, and combustion quenching. The graph represents LGWE in LHR engine that gives very less values in all load conditions, followed by CI engine powered with LGWE. So, it may be asserted that LGWE reduces hydrocarbon emission due to the availability of more oxygen substantialized in it. In maximum load condition, the diesel fuel in CI and LHR engines emits 74 ppm and 71 ppm of hydrocarbon, respectively, and this is reduced

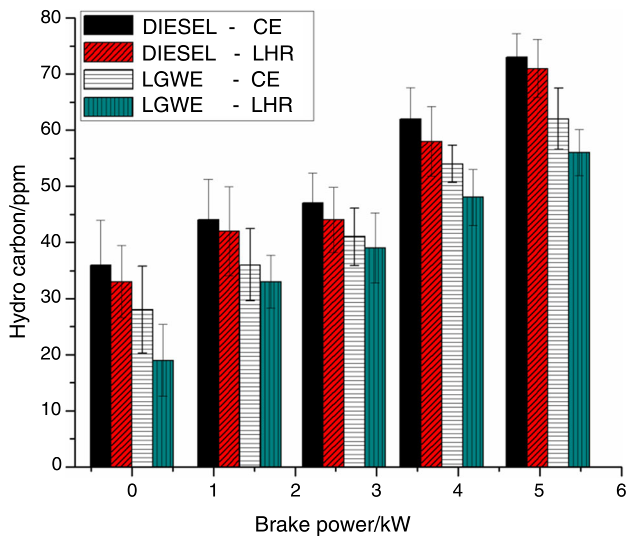


Fig. 9 Variation of lemongrass oil–water emulsion and its blend on HC

by LGWE in CI and LHR engines to 63 ppm and 57 ppm, respectively.

Carbon monoxide (CO)

The transformation of oxygen in the combustion chamber causes the emission of carbon dioxide, while the reduced content of oxygen when combusted or chemically bound together with tarrying particles of HC causes the emission of carbon monoxide (CO) [22]. The emission of CO may also be ascribed to various factors including accumulated fuel stagnated regions, air–fuel mixture ratio and incomplete combustion. The emission of CO will always be reduced when cetane number and engine speed are increased. The fuel containing the increased amount of oxygen and reduced emission of HC will always be said to have reduced CO emission. Figure 10 shows the values of CO and brake power (BP). The values from the graph show that at maximum load condition the values of CO are very high in all CI and LHR, but these values are very much low compared with that of the diesel fuel. This is because of the higher air–fuel mixture inflow, thus enabling good combustion and reduced hydrocarbon emission with LGWE fuel. Higher cetane number values and reduced fuel stagnation zone in the combustion chamber facilitate the reduced emission of CO. The values of CO for diesel fuel in CI and LHR engines were observed as 0.20% and 0.17%, respectively, and for LGWE in CI and LHR engines, these values were 0.16% and 0.12% at maximum load condition, respectively. The values of CO emission are very much reduced for LGWE compared with diesel fuel in LHR and CI engines at all load conditions. This is because of secondary atomization process which divided the fuel

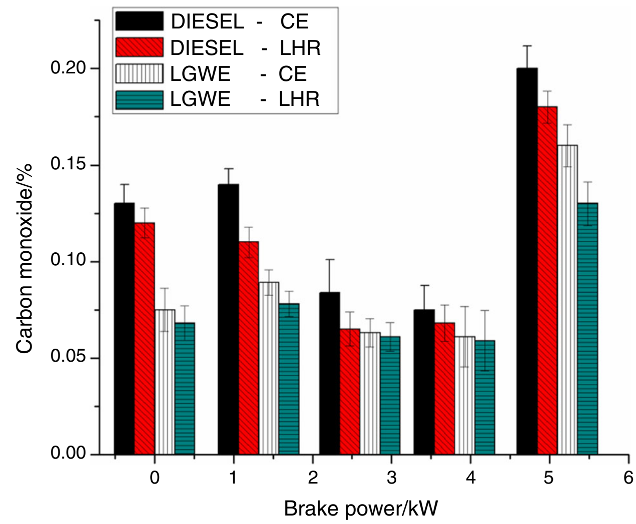


Fig. 10 Variation of lemongrass oil–water emulsion and its blend on CO

into fine beads consequently upgrading the air–fuel blend proportion [23]. The hot surface area took less time to combust the fuel, since the surface reaction of combustion fuel [24].

Carbon dioxide (CO_2)

The emission of CO_2 is due to the entire combustion of HC fuel. CO_2 is one of the most important gases in green house gases (GHG), which promotes the most of the plants' livelihood through photosynthesis. Biofuel emits more CO_2 than a natural diesel fuel [25–29]. CO_2 when liberated through the biofuel is recirculated and used by plants, and in the same case, the diesel fuel emits more carbon content than biofuels which is deposited as carbon atoms in the atmosphere. The higher constituent of O_2 in the biofuel makes it possible to emit CO_2, and in the same case, fossil fuel emits more carbon content; this is due to the high *H*/*C* ratio [30–33]. Figure 11 shows the value of CO_2 emission with respect to brake power for diesel and LGWE as fuel in CI and LHR engines. The values of CO_2 are more for LGWE than for diesel fuel in CI and LHR engines. The values start to ascend for diesel fuel in CI engine, then followed by diesel fuel in LHR, and then, the values increase for CI and LHR powered by LGWE as fuel. At maximum load condition, the values of CO_2 emission vary from 5.7% and 6.0% with diesel fuel in CI and LHR engines and 6.6% and 6.8% with LGWE in CI and LHR engines, respectively.

Nitrogen oxides (NO_x)

CI engines are those that operate at very high temperature and compression ratios, and there is a higher possibility of

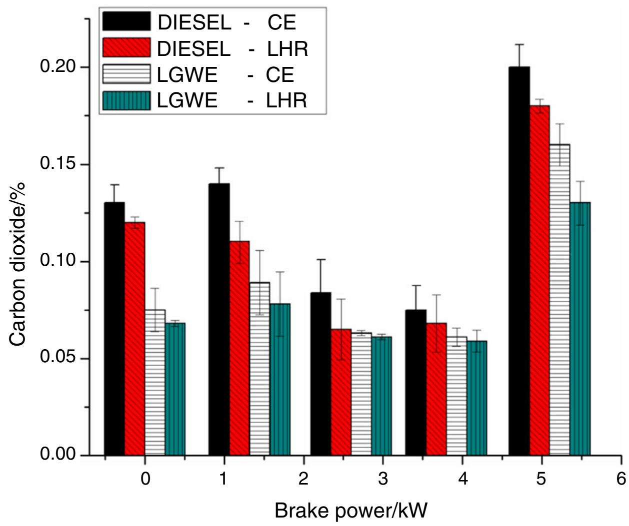


Fig. 11 Variation of lemongrass oil–water emulsion and its blend on CO_2

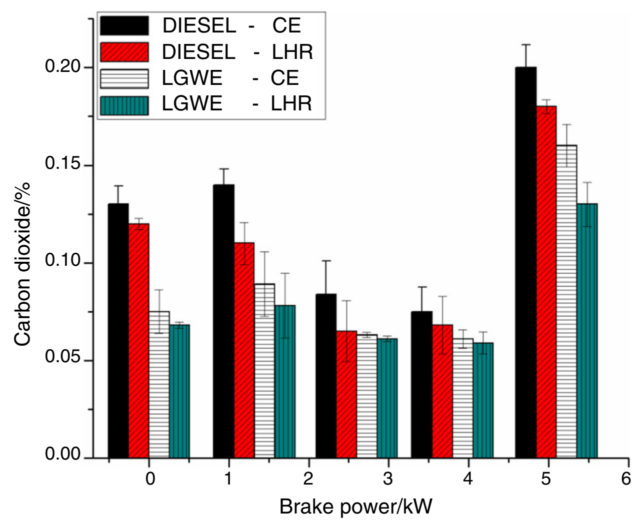


Fig. 12 Variation of lemongrass oil–water emulsion and its blend on NOx

formation of NO_x [34–37]. The NO_x emission is a combination of various chemical compositions or different oxides of nitrogen (including NO_2 and NO) that are emitted when fuel is combusted. Premixture of fuel in combustion phase with higher cetane index value contains more O_2 content and thus reduces the possibility of formation of NO_x [38–40]. The emission of NO_x is dependent on various logical conditions including head transfer coefficient, higher adiabatic combustion temperature, excess heat transfer rate and inclusion of more oxygen. Figure 12 illustrates the variation of NO_x (ppm) with various brake power values (KW) for diesel and LGWE fuel in CI and LHR engines. The emission of NO_x for various load ratios ascending for diesel in CI and LGWE in LHR has a maximum value in ppm. This is due to the availability of more oxygen content in LGWE; the better atomization of LGWE particles produces more heat and lesser heat transfer occurs to the continuous combustion of the fuel, and reduced values in diesel fuel indicate complete combustion of fuel that has a better heat transfer than LHR in CI engine. At the part load condition, there is a drastic reduction in nitrogen oxides emission with lemongrass oil–water emulsion, which is because of the high latent heat of water mixed with emulsified fuel [40–42]. The subsequent values of NO_X in ppm ascend from 710,720 for diesel fuel in CI and LHR engines and 721, 749 for LGWE in CI and LHR engines.

Smoke

Smoke emission of an engine depends upon the load variability of the engine; when the load of an engine is increased, the intake of air gets reduced, which in turns creates a fuel dense mixture; that is to say, air–fuel mixture ratio is higher than the prescribed ratio, which in turn causes smoke emission [43, 44]. Other than that, some reasons of smoke are density of the fuel and viscosity of the fuel that increase the value of these properties and are in direct proportion with smoke emission. The engine loads also have a great effect on smoke emission; the more the load, the more the smoke which causes due to reduced reaction time and more fuel accumulation. Figure 13 indicates high and low smoking points for diesel and LGWE in CI and LHR engines at various load conditions. The LGWE fuel has reduced smoke value in CI and LHR engines. At maximum load condition, the values of smoke emission are subsequently decreased for diesel in CI and

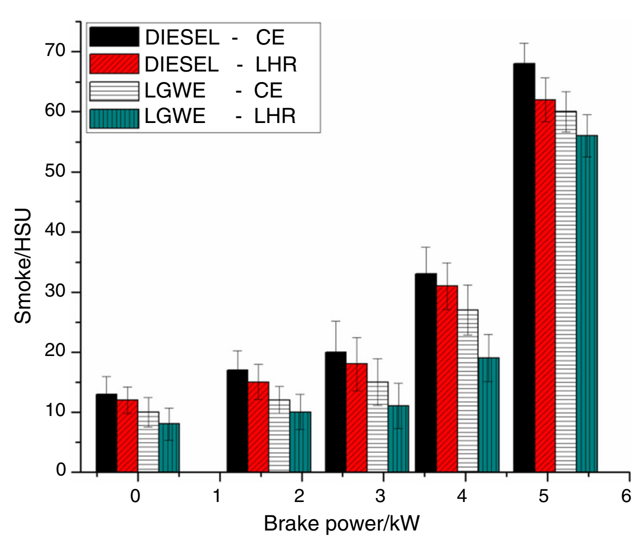


Fig. 13 Variation of lemongrass oil–water emulsion and its blend on smoke opacity

LHR engines compared with those for LGWE with CI and LHR engines, and the consequent values of smoke emission in HSU are 67.5 and 63.0 for diesel in CI and LHR engines and 59.0 and 51 for LGWE in CI and LHR engines, respectively. The major reason for the reduction in smoke emission with the lemongrass oil–water emulsion is the secondary atomization [22].

Conclusions

The performance, combustion and emission characteristics of lemongrass oil–water emulsion by thermal barring coating of diesel engine were studied. The following conclusions were drawn from the present investigation:

- A higher BTE was observed for diesel fuel, i.e. 32% and 29% in coated and uncoated engines, respectively, when compared with all the other tested fuels. The lemongrass oil–water emulsion (LGWE) was found to give a BTE of 27.5%, which is a slightly decreased value when compared with diesel in coated engine, and it can be attributed to induced microexplosion (secondary atomization) of the fuel and LHR coating that improves cylinder temperature, resulting in better evaporation of the fuel and reduced ignition delay.
- The BSFC for LHR diesel engine was found lower (325 g kW^{-1} h^{-1}) than for other tested fuels because it enhanced the rapid evaporation process of water in an oil drop, by breaking up the droplet into fine particles, thus making an improvement in combustion.
- The in-cylinder pressure and HRR were found to be 60 bar and 58 kJ m^{-3} deg^{-1} with coated diesel engine for LGWE, respectively. The values of lemongrass oil–water emulsion in LHR were very close to those of diesel in LHR engine owing to the superior combustion of lemongrass oil–water emulsion in the combustion chamber which led to a slight increase in temperature by the use of thermal barring coating. The CHRR of LGWE in LHR engine was 1370 kJ m^{-3} deg^{-1}, and it was higher with LGWE in CI engine.
- The diesel engine gives a higher HC emission which was found to be 74 ppm, and this was less for LGWE in CI and LHR engines, i.e. 63 ppm and 57 ppm, respectively, because enhanced atomization and vapourization of the lemongrass oil–water emulsion in LHR engine resulted in secondary atomization, which would have led to better blend with air and induced entire combustion of the fuel.
- The diesel fuel in CI and LHR engines yielded higher CO emission of 0.20% and 0.17% than the LGWE in CI and LHR engines of 0.16% and 0.12% emissions, respectively, at maximum load condition. It was because of secondary atomization process which converted fuel into fine droplets, thus enhancing the air–fuel mixing process.
- Both CO_2 and NO_x emissions were observed to be higher for LGWE with diesel fuel in uncoated and coated engines. But on the contrary, smoke emission was comparatively lower for LGWE in uncoated engine and LHR engines owing to microexplosion in emulsified fuel that led to instantaneous vapourization of water droplets available in the fuel droplet.

Hence, the uncoated engine and LHR engines powered by lemongrass water emulsion deserve loser range of performance and combustion. The integrated effect of LGWE in uncoated engine and LHR engines results in higher range of CO_2 and NO_x emission. But HC and CO followed by smoke emissions of LGWE in uncoated engine and LHR engines were dramatically reduced. Thus, the test fuel LGWE can be recommended as an effective alternative fuel for CI and LHR engines.

Acknowledgements The author sincerely thanks Dr. K. Annamalai, Ph.D. Assistant Professor, Department of Automobile Engineering, Anna University (MIT Campus), for his valuable guidance throughout the research work. The author also thanks Dr. V. P. Ramamoorthy, former Professor of Anna University and present Managing Trustee of Dhanalakshmi College of Engineering, for his motivation and support for the research work.

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