COMBUSTION AND EMISSION CHARACTERISTICS OF A DUAL FUEL ENGINE OPERATED WITH MAHUA OIL AND LIQUEFIED PETROLEUM GAS

by

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For the present work, a single cylinder diesel engine was modified to work in dual fuel mode. To study the feasibility of using methyl ester of mahua oil as pilot fuel, it was used as pilot fuel and liquefied petroleum gas was used as primary fuel. In dual fuel mode, pilot fuel quantity and injector opening pressure are the few variables, which affect the performance and emission of dual fuel engine. Hence, in the present work, pilot fuel quantity and injector opening pressure were varied. From the test results, it was observed that the pilot fuel quantity of 5 mg per cycle and injector opening pressure of 200 bar results in higher brake thermal efficiency. Also the exhaust emissions such as smoke, unburnt hydrocarbon and carbon monoxide are lower than other pressures and pilot fuel quantities. The higher injection pressure and proper pilot fuel quantity might have resulted in better atomization, penetration of methyl ester of mahua oil and better combustion of fuel.

Key words: *alternative fuel, dual fuel engine, pilot fuel, injector opening pressure, performance, emission*

Introduction

During recent years high activities can be observed in the field of alternative fuels, due to supply of petroleum fuels strongly depends on a small number of oil exporting countries. As far as low emission fuels are concerned, "gaseous fuels" appear to be capable of performing a prominent role. Various gaseous fuels such as biogas, producer gas (wood gas, produced in a gasifier), hydrogen, liquefied petroleum gas (LPG), and compressed natural gas (CNG) are suitable for internal combustion engines. But LPG and CNG are considered better alternatives because of their simpler structure with low carbon content, resulting in reduction of exhaust emissions drastically. In India, LPG is easily available compared to CNG. Hence, for the present work LPG is taken as gaseous fuel. Since diesel is a non-renewable fuel, biodiesel can be used as substitute for diesel in dual fuel mode. In dual fuel engine, the primary fuel releases large amount of energy and secondary fuel or pilot fuel is required to start the combustion of the primary fuel.

Karim [1] have made comprehensive studies of combustion phenomena in gas fuelled single cylinder diesel engines, mostly DI diesel engine. He observed that LPG results in poor performance at light loads. It was found that CO and unburnt hydrocarbon (UBHC) concentrations increased rapidly at light loads compared to those normally measured in diesel engines, with propane having higher concentration than methane. Karim attributed this to the fact that the ignition delay period of the pilot diesel fuel is much higher during propane fumigation than that with methane. Beyond half load, however, efficiency improved and surpasses that of diesel fuel at full load. Here, propane was found to be a better fuel than methane. He also noted that a reduction in peak cylinder pressure, fumigation of methane and propane produced lower concentration of NO_x, particularly at higher loads. Poonia *et al*. [2] studied the effect of intake air temperature and pilot fuel quantity on the combustion characteristics of a LPG diesel dual fuel engine. They considered pilot quantities of 3.36, 4.6, 5.9, 7.5, 8.4, and 10.7 mg per cycle and the compression ratio of 15:1.

Sethi *et al*. [3] studied the performance and emission of LPG diesel dual fuel engine. They reported that the dual engine performance is comparable with diesel (sole fuel) operation at higher loads. But oxides of nitrogen emissions were higher than neat diesel operation. They also reported that the exhaust emissions such as CO, UBHC, and SO_2 emissions were reduced by 80, 71, and 21%, respectively.

Hitoshi [4] studied the combustion phenomena and ignition characteristics by visualizing the combustion chamber while the engine is operated under the dual combustion mode. They used an open chamber type single cylinder research engine together with an endoscope suitable for observing a small space. From the experimental results they observed that the pilot fuel is ignited around the nozzle tip due to less penetration of pilot fuel. After pilot fuel is auto ignited, the pilot flame propagates to the lean gas pre mixture rapidly. They also reported that the ignition delay and combustion intensity of pilot fuel is influenced by partial pressure of oxygen in the fresh air when injection condition and compression end temperature are kept constant. Weidong *et al*. [5] used pilot diesel injection (PDI) in an homogenous charge compression ignition (HCCI) engine to decrease the required intake temperature. A small amount of diesel was injected into the cylinder early in the compression stroke for a natural gas fuelled HCCI engine. They found that the PDI-HCCI concept could reduce the required initial temperature by about 70 K compared to the conventional HCCI engine. They also found that the performance of the HCCI engine became less sensitive to initial temperatures in the PDI-HCCI combustion process compared to the conventional HCCI engine case.

Mohanan *et al*. [6] studied the effect of cycle variation on the performance of the LPG diesel dual fuel engine. They found that for LPG flow rates between 0.2 to 0.3 kg/h fluctuations in various parameters like peak pressure, rate of pressure rise and indicated mean effective pressure is minimum, because the combustion is mainly due to diesel fuel and relative lean mixture of diesel and air burns efficiently. At LPG flow rate beyond 0.3 kg/h the fluctuations in performance parameters increase due to the fact that combustion is not efficient because mixture being very lean. But the best result is obtained at flow rates between 0.5 to 0.6 kg/h. They concluded that at full load fluctuations in indicated mean effective pressure indicated thermal efficiency and peak pressure remains steady-state at low value for most of the LPG flow rates.

Kapilan *et al*. [7] studied the performance and emission of a LPG biodiesel dual fuel engine. They used methyl ester of sunflower oil as pilot fuel and LPG as primary fuel. They reported that the performance and emission of the dual fuel engine is comparable with diesel engine at higher loads. Sukumar *et al*. [8] used methyl ester of mahua oil as sole fuel in diesel engine. They prepared mahua oil ethyl ester (MOEE) by transesterification method using sulfuric acid (H_2SO_4) as catalyst and MOEE was tested in a 4-stroke direct injection natural aspirated diesel engine. Tests were carried out at constant speed of 1500 rpm. They reported that the performance of MOEE was comparable with diesel operation and emissions such as CO, HC, NO_x, and smoke were lower than diesel operation.

Mahua trees are grown in drought prone areas and are abundant in several parts of India. Use of methyl ester of mahua oil (MEMO) as the renewable substitute fuel for diesel will reduce the diesel consumption and it will conserve India's foreign exchange. The availability of mahua oil seed is 30,000 metric tons. As per an estimate, India consumed about 40.34 million tons of diesel in 2000-2001, which was 43.2% of the total consumption of petroleum products and two thirds of the demand was met by import costing about USD 5 billion [9]. With an expected growth rate of diesel consumption of more than 14% per annum, shrinking crude-oil reserves and limited refining capacity, India will have to depend heavily on imports of crude. Hence, Indian government is planning of producing biodiesel from non-edible oils. The objective of this is to conserve foreign exchange, utilization of wastelands to sustainable use, conserve ecosystem and biological diversity.

Present work

For the present work, MEMO was prepared by transesterification method. The fuel properties of the MEMO were determined and compared with the diesel. From the comparison, it is observed that the properties of MEMO are close to diesel. The properties of MEMO and diesel oil are shown in tab. 1.

In India, LPG is easily available as compared to other gaseous fuels. Hence LPG was used as primary fuel. The composition and properties of LPG is shown in tab. 2.

Table 1. Properties of mahua oil, MEMO, and diesel

Property	MEMO	Diesel
Flash point [°C]	129	56
Fire point [°C]	141	63
Calorific value [MJ/kg]	36.14	42.96
Kinematic viscosity at 40 °C [Cst]	5.10	2.68
Density at 40 °C [kg/m^3]	863	828
Cetane number	49	51

Table 2. Properties of LPG

Property	Value
Composition (by vol.%) N-butane, iso butane and butylenes Propane and propylene Ethane and ethylene Pentane	 70.4% 28.6% 0.5% 0.5%
Calorific value [MJ/kg]	47.88
Maximum flame temperature in air [°C]	2000
Self ignition temperature [°C]	525

In dual fuel mode, MEMO was used as pilot fuel and LPG was used as primary fuel. The injector opening pressure recommended for diesel operation is 180 bar. Since the viscosity of MEMO is higher than diesel, higher pressures such as 200 and 220 bar were selected. To study the effect of pilot fuel quantity, four pilot fuel quantities such as 3.88, 5, 6.11, and 7.22 mg per cycle (19.4, 25, 30.51, and 36.1% of full load MEMO) were considered.

Experimental setup

The details of the engine used for the present work are given in tab. 3. The schematic of the experimental setup is shown in fig. 1.

A single cylinder, four stroke, water cooled, naturally aspirated, direct injection diesel engine was modified to work in dual fuel mode. An eddy current dynamometer was used for loading the engine. The engine speed was sensed and indicated by an inductive pick up sensor in

Table 3. Engine details

Engine	4, single cylinder, water cooled engine
Make/model	Kirloskar TV 1
Maximum power output	7 BHP at 1500 rpm
Bore stroke	87.5 110 mm
Compression ratio	17.5 :1
Injection timing	27 deg bTDC
Fuel pump	Mechanical plunger pump
Nozzle injector	Single hole fuel injector

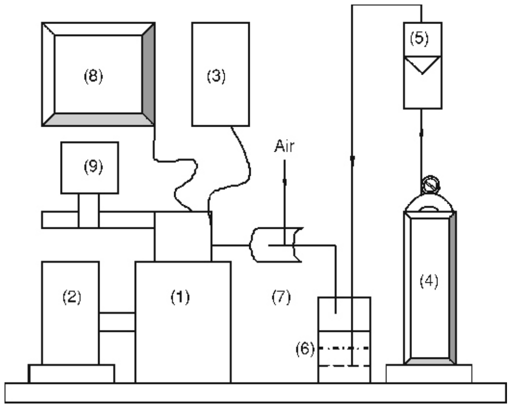

Figure 1. Experimental setup
(1) – Engine, (2) – Dynamometer, (3) – Fuel tank, (4) – LPG cylinder, (5) – Rotameter, (6) – Flame arrestor, (7) – Fuel and air mixing chamber, (8) – Data acquisition system, (9) – Emission analyser

conjunction with a digital rpm indicator, which is a part of eddy current dynamometer. The diesel fuel flow rate was measured on the volumetric basis using a burette and a stopwatch. Chromel alumel thermocouple in conjunction with a digital temperature indicator was used for measuring the exhaust gas temperature. The gas flow rate was measured using a rotameter with duralumin float. AVL 437 smoke meter was used to measure the smoke emission and DELTA 1600 L of MRU make exhaust gas analyzer was used for the measurement of emissions in exhaust gases. For the cylinder pressure and crank angle measurement, a pressure transducer was fitted on the engine cylinder head and a crank angle encoder was fixed on the engine shaft, respectively. The pressure and crank angle signals were fed to a data acquisition card fitted with Pentium 4 personal computer.

Experimental procedure

The diesel engine was modified to work in the dual fuel mode by attaching an LPG line to the intake manifold. The pilot MEMO flow rate and LPG flow rate were varied by adjusting the fuel injection pump and the flow control valve, respectively. All tests were conducted at a constant speed of 1500 rpm and at full load. First set of tests was conducted at the injector opening pressure of 180 bar. The engine was started by hand cranking with MEMO as fuel and slowly LPG was introduced to the cylinder, through the intake manifold and the load was gradually increases to full load. The pilot MEMO flow rate was maintained constant at 3.88 mg per cycle and the engine speed was maintained at 1500 rpm, by adjusting the LPG flow rate. At steady-state condition, important observations such as LPG flow rate, air flow rate, exhaust gas temperature, cylinder pressure, and emissions were recorded. Then the pilot fuel quantity was increased to 5 mg per cycle and important observations were recorded. Similar procedure was followed for the pilot fuel quantity of 6.11 and 7.22 mg per cycle. After the completion of first set of tests, injector opening pressure was increased to 200 bar and then to 220 bar.

Result and discussion

The result of the experiments conducted in diesel and dual fuel modes are discussed below.

The variation of cylinder pressure with pilot quantity at different injector opening pressures is shown in figs. 2-5. From fig. 2, it is observed that the fuel injector opening pressure of 220 bar results in sudden pressure rise. This may be due to poor penetration of small quantity of pilot fuel, which results in accumulation of fuel nearer to the injector. This results in delay in combustion of the LPG. The sudden combustion of the LPG results in higher pressure rise. The pilot fuel quantity of 5 mg per cycle results in smooth pressure rise. But the pressure rise is not smooth for the pilot fuel quantity of 6.11 and 7.22 mg per cycle.

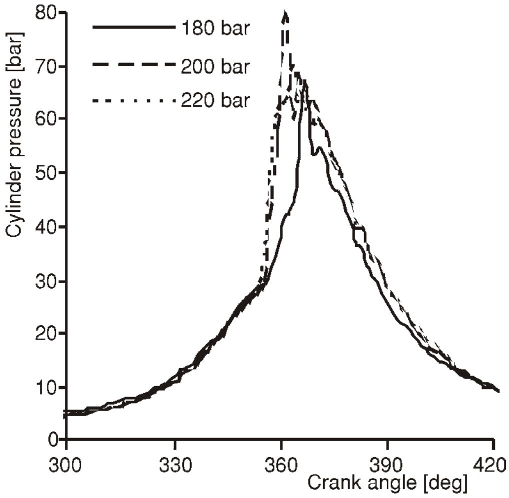

Figure 2. Pressure *vs.* crank angle at 3.88 mg per cycle

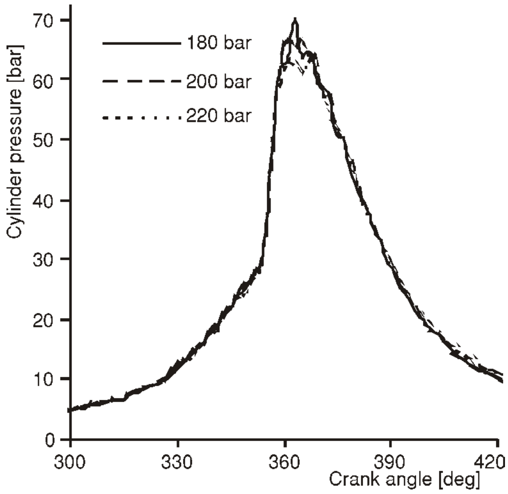

Figure 3. Pressure *vs.* crank angle at 5 mg per cycle

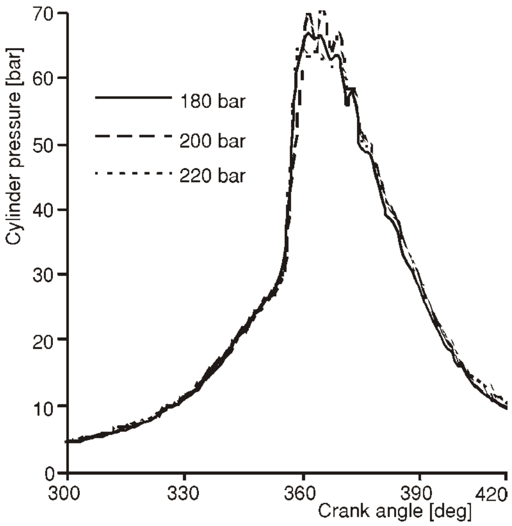

Figure 4. Pressure *vs.* crank angle at 6.11 mg per cycle

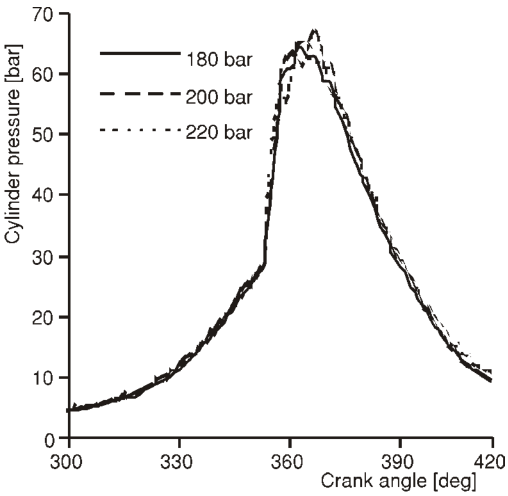

Figure 5. Pressure *vs.* crank angle at 7.22 mg per cycle

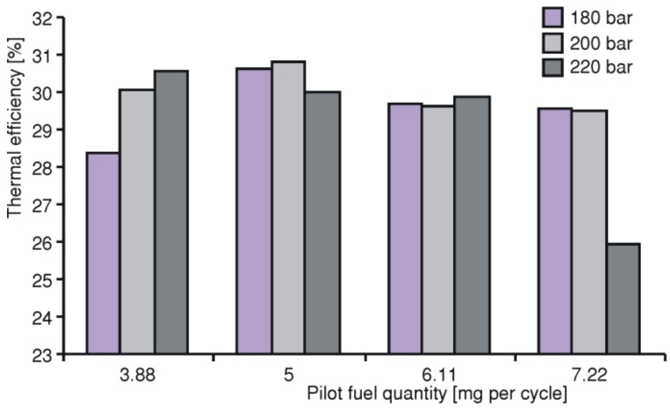

Figure 6. Thermal efficiency *vs.* pilot fuel quantity

Figure 6 shows the variation of brake thermal efficiency at different pilot fuel quantities. The brake thermal efficiency of diesel baseline at full load is 30.04%. The pilot fuel quantity of 5 mg per cycle results in higher brake thermal efficiency at the injector opening pressure of 200 bar. This may be due to better combustion of the fuel and the cylinder pressure *vs.* crank angle diagram also shows the same trend. The pilot fuel quantity of 7.22 mg per cycle, results in lower brake thermal efficiency, at the injector opening pressure of 220 bar. This may be due to higher injector opening pressure, which might have resulted in scattered injection of pilot fuel. This poor injection of fuel results in poor fuel utilization and increased fuel consumption. This leads to poor brake thermal efficiency.

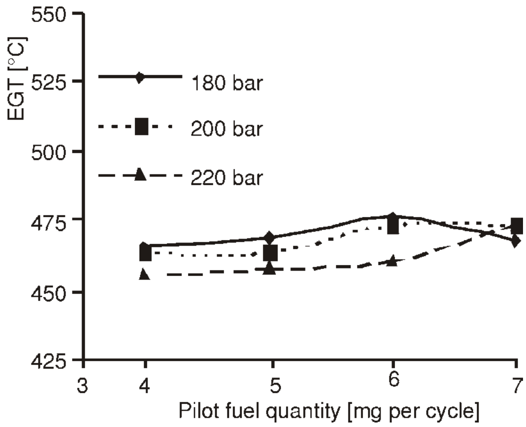

Figure 7. EGT *vs.* pilot fuel quantity

The variation of exhaust gas temperature (EGT) with load at different pilot fuel quantity is shown in fig. 7. The injector opening pressure of 180 bar results in higher EGT. This may be due to injection of pilot fuel at low pressure. This results in higher ignition delay and slow combustion of the fuel. This slow combustion results in higher combustion temperature and hence higher EGT. The injector opening pressure of 220 bar results in lower EGT up to the pilot fuel quantity of 6.11 mg per cycle. The diesel mode results in EGT of 432 °C at full load.

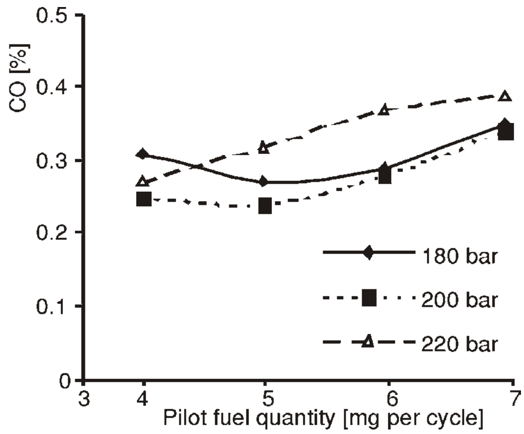

Figure 8. CO *vs.* pilot fuel quantity

The variation of CO emission with pilot fuel quantity is shown in fig. 8. It is observed that the injector opening pressure of 200 bar results in lower CO emission at the pilot fuel quantity of 5 mg per cycle. This may be due to the better and complete combustion of the fuel. The higher CO emission was observed at the pilot fuel quantity of 7.22 mg per cycle for all the injector opening pressure. This may be due to the knocking, which results in scarcity of oxygen. The flame quenching and cooled layer of LPG near the cylinder wall will also be the reason for the increased CO emission. The diesel mode results in CO emission of 0.21% at full load.

The variation of HC emission with pilot fuel quantity at different injector opening pressure is shown in fig. 9. The injector opening pressure of 220 bar results in higher HC emission from the pilot fuel quantity of 5 to 7.22 mg per cycle. This may be due to the abnormal combustion of the fuel, which results in higher HC emission. But for all the injector opening pressures, the pilot fuel quantity of 7.22 mg per cycle results in higher HC emission. This may be due to induction of higher quantity of pilot fuel. The injector opening pressure of 200 bar results in lower HC emission. The lowest HC emission was observed between the pilot fuel quantity of 5 mg per cycle and 6.11 mg per cycle. The diesel mode results in UBHC emission of 486 ppm at full load.

Figure 10 shows the variation of NO_x emission with pilot fuel quantity at different injector opening pressure. It is observed that the, the injector opening pressure of 200 bar results in higher NO_x emission. This may be due to the higher heat release during second stage of combustion, higher combustion temperature and higher heat content of the LPG. The presence of high gas temperature inside the cylinder will create a conducive ambient for reaction of nitrogen in air with oxygen. The injector opening pressure of 220 bar results in lower NO_x emission. This may be due to the poor combustion of the fuel which results in lower combustion temperature and hence lower NO_x emission. The diesel mode results in NO_x emission of 915 ppm at full load.

Figure 11 shows the variation of smoke emission with pilot fuel quantity. It is observed that the injector opening pressure of 220 bar results in higher smoke emission. This may be due to knocking which results in non availability of sufficient oxygen for the combustion of fuel. The injector opening pressure of 200 bar results in lower smoke emission at the pilot fuel quantity of 5 mg per cycle. This may be due to the availability of premixed and homogenous fuel inside the cylinder, before the commencement of combustion. Higher heat content of LPG, higher combustion temperature, extended duration of

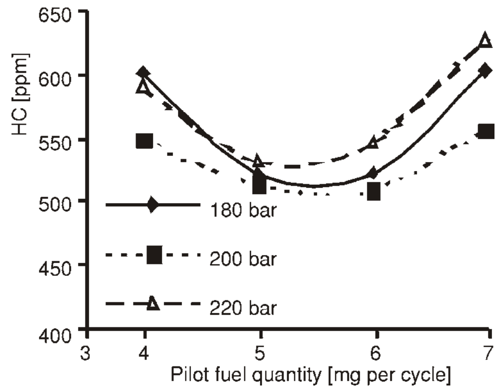

Figure 9. HC *vs.* pilot fuel quantity

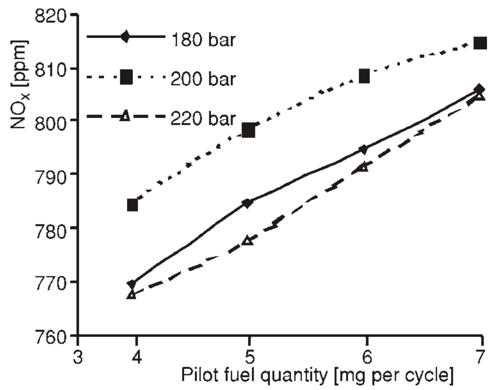

Figure 10. NO_x *vs.* pilot fuel quantity

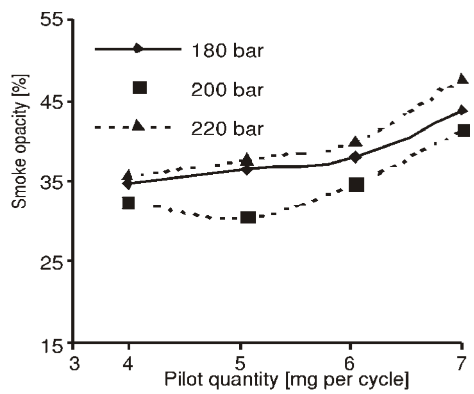

Figure 11. Smoke *vs.* load

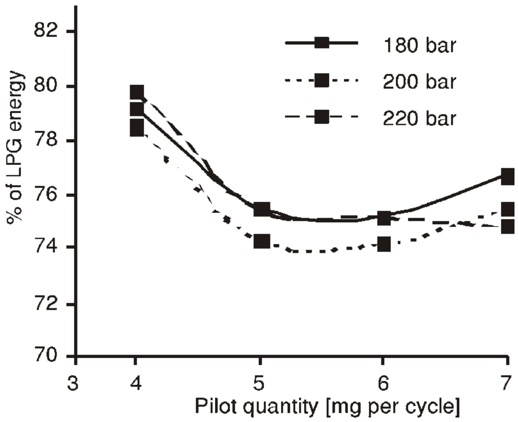

Figure 12. LPG energy *vs.* pilot quantity

combustion and rapid flame propagations are the other reasons for the reduced smoke level. The diesel mode results in smoke emission of 43.5% at full load.

Figure 12 shows the variation of LPG energy with pilot fuel quantity at different injector opening pressures. It is observed that the injector opening pressure of 200 bar requires less LPG energy as compared to other injector pressures. But the injector pressure of 220 bar requires higher LPG energy at low LPG pilot quantity and lower LPG power at higher pilot fuel quantity. Also there is a slight variation in LPG energy of 180 and 220 bar.

Conclusions

From the test results, the following conclusions are drawn.

(1) Engine runs smoothly with the pilot fuel quantity of 5 and 6.11 mg per cycle and at the injector opening pressure of 200 bar.
(2) Knocking was observed at the pilot fuel quantity of 7.22 mg per cycle, for all the injector opening pressure.
(3) The combination of pilot fuel quantity of 5 mg per cycle and the injector opening pressure of 200 bar results in higher brake thermal efficiency and lower CO, HC emissions. But this combination results in higher NO_x emission.
(4) From the experimental results it is concluded that MEMO can be used as a substitute for diesel in dual fuel engine with the pilot fuel quantity of 5 mg per cycle and at the injector opening pressure of 200 bar.

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Nomenclature

BHP – brake horse power
EGT – exhaust gas temperature
HCCI – homogenous charge ignition engine
LPG – liquefied petroleum gas
MEMO– methyl ester of mahua oil
MOEE – mahua oil ethyl ester
PDI HCCI – pilot diesel injection homogenous charge ignition engine
UBHC – unburnt hydrocarbon

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