EXPERIMENTAL INVESTIGATION OF EVAPORATION RATE AND EMISSION STUDIES OF DIESEL ENGINE FUELLED WITH BLENDS OF USED VEGETABLE OIL BIODIESEL AND PRODUCER GAS

by

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Original scientific paper
DOI: 10.2298/TSCI150604106B

An experimental study to measure the evaporation rates, engine performance and emission characteristics of used vegetable oil methyl ester and its blends with producer gas on naturally aspirated as vertical single cylinder water cooled four stroke single Diesel engine is presented. The thermo-physical properties of all the bio fuel blends have been measured and presented. Evaporation rates of used vegetable oil methyl ester and its blends have been measured under slow convective environment of air flowing with a constant temperature and the values are compared with fossil diesel. Evaporation constants have been determined by using the droplet regression rate data. The fossil diesel, biodiesel blends and producer gas have been utilized in the test engine with different load conditions to evaluate the performance and emission characteristics of diesel engine and the results are compared with each other. From these observations, it could be noted that, smoke and hydrocarbon drastically reduced with biodiesel in the standard diesel engine without any modifications.

Key words: *used vegetable oil, biodiesel, fossil diesel, evaporation rate, engine performance, emissions*

Introduction

In recent years, a growing interest is found on the research concerning renewable and alternative fuels. These fuels are bio-degradable and oxygenated and the examples include vegetable oils, their derivatives and their mixtures with fossil diesel. Research on vegetable oil in diesel engine was conducted at least 100 years back. Due to availability of fossil diesel, the research on vegetable oil based engine fuels lost importance with time. In present time scenario, due to the price hike of fossil diesel, the research on biodiesel has again gained importance [1]. Neat biodiesel and its different blends were effectively fueled in single cylinder diesel engine for shaft power applications without any major modifications [2-9]. Multi cylinder diesel engine was also successfully operated with biodiesel and its blends [10, 11].

It could be clearly stated that several studies have been carried out with vegetable oil biodiesel as an alternative fuel in an internal combustion engines. Only direct applications of

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vegetable biodiesel in engines have been presented in detail since the performance and emission characteristics are mainly depend on its physical properties. For any liquid fuel apart from the thermo-physical properties, an important parameter is the rate at which it can vaporize within several ambient conditions. To carry out evaporation studies, a suspended droplet experiment has been setup and evaporation rate constants for used vegetable oil biodiesel and its blends have been estimated. This suspended droplet evaporation study will not provide direct vaporization characteristics inside an actual engine, but will be useful for fuel characterization study, since it gives the difference in the evaporation features between several blends. Evaporation characteristics of multi-component fuels and vegetable oils have been reported in literature [12, 13]. The vaporization of an ethanol droplet is accompanied by the simultaneous condensation of water vapour on the droplet surface and thus the temporal evolution of the droplet squared diameter exhibits an unsteady behavior. The same has been calculated from the $d^2(t)$ curves which confirms this *non-stationary* aspect of the phenomenon [14]. In the present study, used cooking oil is used as a raw material for biodiesel production by transesterification process. For maintaining 20% of energy content from the fossil diesel, the blend of 23% of biodiesel and 73% of fossil diesel (B23) is used in this experiment. This work has been describing the thermo-physical properties, evaporation studies of biodiesel blends in the form of B0 and B23, engine performance and emission characteristics with producer gas combination.

Experimental set-up and procedure

Evaporation studies

Suspended droplet experiments are carried out to estimate the evaporation rates of used vegetable oil methyl ester and its blends. Figure 1 shows the schematic of the experimental set-up. Heated air at a constant volumetric flow rate flows through a ceramic pipe having an internal diameter of $19 \cdot 10^{-3}$ m. A pre-calibrated rotameter is used to control the volume flow rate of air to the electric heater. Within a distance equal to the internal diameter of the pipe, a suspended droplet is introduced. Droplet is suspended over a thin stainless steel (SS) wire having a diameter of $0.28 \cdot 10^{-3}$ m. High-speed digital video of the droplet is taken until the entire droplet vaporizes. As it was not possible to create the pressure condition in the engine, this is only a relative study for comparison, the air velocity and temperature values are kept as 0.23 m/s and 300 °C, respectively. The stainless steel wire is cooled by water flow through copper tube jackets braced over its surface for a significant length. This is used to avoid heating up of the wire and to prevent the heat transfer from the wire to the droplet.

The regression of fuel droplet diameter is captured in a high-speed digital camera for determining the evaporation characteristics of the testing fuel droplet. In high-definition mode, the maximum images that could be taken per second are 60. Due to trade-off between number of images per second and clarity of the obtained images, videos are recorded at 30 frames per second in high-definition mode. The captured video is extracted into digital images. The digital images are processed using MATLAB 7.0 to determine the droplet diameter at every time instant. Ambient temperature condition is measured using a K-type thermocouple connected to a digital temperature indicator. Thermocou-

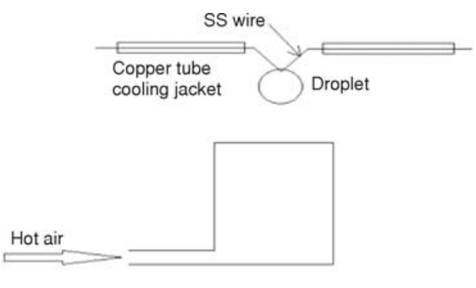

Figure 1. Schematic diagram of experimental set-up for droplet evaporation studies

ple has been kept exactly at the same position where droplet had to suspend to minimize any possibility of difference in measured and existing ambient test temperature. Operating range of K-type thermocouple is – 45-1000 ºC. The camera has been kept at 180° position with respect to droplet. The thermocouple has been kept just above the hot air tube and below the droplet. The suspension droplet by gravity action has been studied. Average diameter has been determined as $2.16\cdot10^{-3}$ m. Ambient pressure has been fixed as barometric pressure of 1.01325 bar. This study has been taken at steady-state condition.

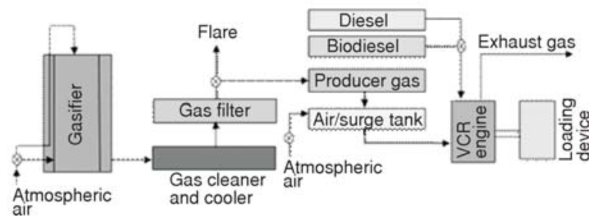

Figure 2. Schematic diagram of gasifier unit and engine set-up

Engine studies

The experimental system consists of a gasifier, water scrubber, cyclone separators, organic filter, fabric filter, gas balloons, and diesel engine with eddy current dynamometer loading device. The schematic diagram represents the experimental set-up in fig. 2.

In this present work naturally aspirated four stroke single cylinder water cooled direct injection variable compression ratio (VCR) compression ignition engine is used. The engine is run with an optimized compression ratio of 18. The conventional fuel injection nozzle which has three holes with a diameter of 0.3 mm with a spray angle of 120° is used. As the fuel is injected around 23° befor top dead contre (bTDC) and fuel injection pressure of 200 bar at rated speed of 1500 rpm, it may be noted that the flow velocities will be quite small near the injector and the temperature will be around 327 °C. Engine is coupled with a loading device eddy current dynamometer and all the sensors are connected to the data logger system. The specifications of the engine are shown in tab. 1.

Table 1. Specifications of the engine

Make	Legion Brothers – Modified Kirloskar AV1
Type	New single cylinder four stroke naturally aspirated water cooled direct injection, vertical, VCR Engine
Bore × Stroke	80 mm × 110 mm
Stroke volume	0.553 litre
Compression ratio (variable)	5:1-20:1
Standard compression ratio	16.5:1
Standard fuel injection timing by spill	23° bTDC
Standard nozzle opening pressure	200-205 bar
Ratting	3.7 kW
Engine speed	1450-1600 rpm
Loading device	Eddy current dynamometer
Software	Engine test express V5.76

A modified small scale gasification system consists of a double walled fixed bed downdraft gasifier is used to produce gas. The cooling tower, cyclone separator, and fabric filter

Table 2. Percentage of uncertainties

Description of instruments and calculated parameters	Uncertainties [%]
Brake power	±0.5
Brake thermal efficiency	±1.16
Burette for fuel measurement	±1.5
Crank angle encoder	±0.2
Digital stop watch	±0.2
Evaporation rate constant	±0.01
Exhaust gas analyzer	±0.2
Fuel consumption	±0.25
Load indicator	±0.5
Manometer	±1.0
Pressure pick up	±1.0
Smoke intensity	±1.0

ensure high quality producer gas with an average composition of combustible gases H_2 – 12.31%, CO – 10.13%, CH_4 – 1.48%, non-combustible gases CO_2 – 14.58%, O_2 – 2.7%, and organic N_2 – 58.80% with a mean calorific value of 3560 ± 50 kJ/Nm^3. The producer gas is collected in a gas bags and supplied to the engine through air surge tank to ensure uniform gas quality throughout this experiment.

The experiment is carried out on the engine with fossil diesel, biodiesel, fossil diesel + producer gas and biodiesel + producer gas at different load conditions. In this present work, eddy current dynamometer is used as a loading device and U-type manometer, load cell, MMW air fair smoke meter, AUTO-CHRO WIN gas chromatography, K-type thermocouples, hot wire mass air flow sensor, optical slot sensor, crank angle encoder, piezoelectric pressure transducer and rotameters are used to measure the air and gas flow rates to the gasifier and engine, the applied load on the engine, opacity of exhaust gas, gas composition, temperatures, mass of air flow rate, fuel flow rate, engine crank angle, combustion pressure and water flow rate, respectively. Uncertainty is a measure of accuracy of the results obtained which is presented in tab. 2

Thermo-physical properties of used vegetable oil biodiesel and its blends

From tab. 3, it is clear that specific gravity, acidity, kinematic viscosity, flash point, fire point, and cloud point increases as the biodiesel content in the biodiesel-diesel blends increases. Especially, the significant increase in the fire point shows that the volatility of the mixture having increased biodiesel content will decrease. The gross calorific value decreases as the

Table 3. Properties of used vegetable oil biodiesel and its blends

Properties of used vegetable oil biodiesel	B100	B80	B60	B40	B23	B20	B0
Kinematic viscosity at 40 °C [cst]	17.5	12.6	9.41	6.48	4.74	4.54	3.24
Flash point [°C]	98	81	77	72	63	61	56
Fire point [°C]	106	88	83	78	69	66	61
Cetane number	51.8	52.1	52.2	52.4	52.6	52.6	52.4
Density at 15 °C [gcc^{-1}]	0.898	0.883	0.865	0.852	0.842	0.840	0.826
Gross calorific value [kJkg^{-1}]	38960	40446	41135	42371	43409	43510	44690
Acidity mg of [KOHg^{-1}]	0.033	0.028	0.026	0.024	0.023	0.021	0.012
Cloud point [°C]	+12	+8	+5	+1	–6	–6	–8
Copper strip corrosion for 3 hours	Not worse than No: 1 passes the test						

biodiesel in the mixture increases. This is due to the oxygen content in the fuel and it requires more fuel to be burnt for a given heat release.

Results and discussion

Evaporation studies

Figure 3 shows the decrease in the droplet diameter with time when it is subjected to an air flow with constant temperature and velocity. Due to changes in the viscosities and surface tension values of the fuel blends, the initial droplet formed has different diameter values. The droplets have been captured at 300 °C temperature for the entire experiment. In this study, an overall average diameter of around $2.16 \cdot 10^{-3}$ m has been obtained. It is clear that the time taken by pure diesel droplet (B0) to evaporate completely is much smaller than B23.

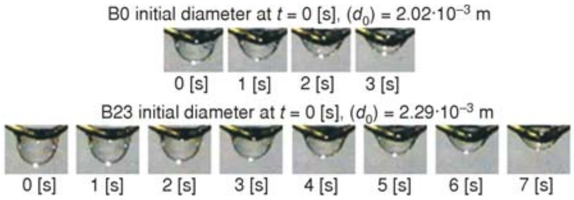

Figure 3. Droplet diameter regression with time for fossil diesel and blend of biodiesel

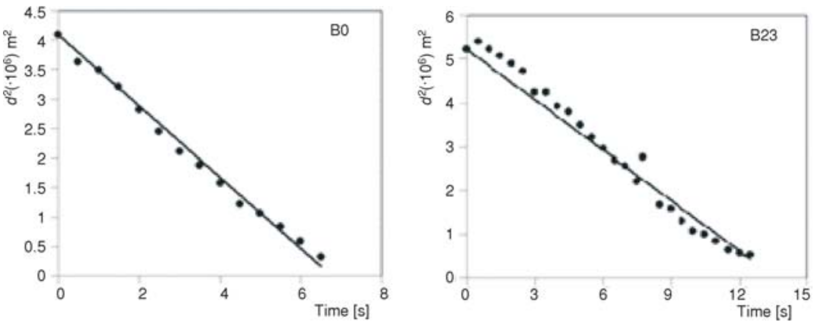

Figure 4. Regression of square of droplet diameter with time for various fuels

The slopes of the linear trend lines shown in fig. 4 represent the evaporation rate constant (K) values. If the trend line is extrapolated to touch the x-axis, the corresponding time will be called droplet evaporation lifetime (t_d). It is clearly observed that the evaporation rate constant decreases and the evaporation lifetime increases as biodiesel is added to fossil diesel. However, the exact trends in the variations of evaporation life constant and droplet lifetime are not apparent from fig. 4. The values of K and t_d are presented in tab. 4.

Table 4. Comparison of evaporation rate constant and evaporation time

S. no	Blend ratio	Evaporation rate constant 10^6 [m^{2}s^{-1}]	Evaporation time [s]
1	B0	0.65	6.2
2	B23	0.41	12.5

Engine studies

Performance characteristics

Figure 5 shows the effect of load on brake thermal efficiency for single fuel and mixed fuel mode operations. It clearly indicates that the brake thermal efficiency for mixed fuel mode operation is lower than the single fuel

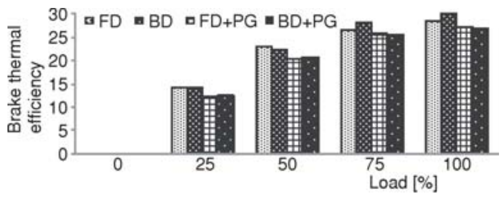

Figure 5. Brake thermal efficiency *vs.* load

mode due to the slow burning nature of producer gas [15]. Moreover the producer gas contains lowest percentage of combustible gasses and large fraction of inert gases such as carbon dioxide and nitrogen which affect the combustion process. Also the induction of producer gas to the engine reduces the fresh air intake to the engine which is a hindrance for combustion process. In the single fuel mode the brake thermal efficiency with biodiesel is on par with fossil diesel in the sense the better combustion due to oxygenated biodiesel as well as additional lubricity provided by the biodiesel reduces the frictional losses [3, 16]. At full load condition the brake thermal efficiency of fossil diesel, fossil diesel + producer gas, biodiesel and biodiesel + producer gas are 28.51, 27.23, 29.94, and 26.77, respectively. Similar observations have also been reported by many researchers [16-18].

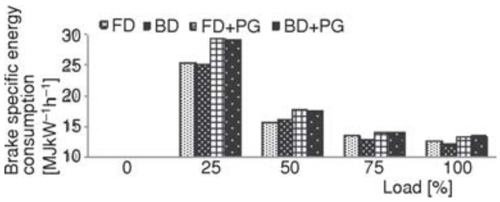

Figure 6. Brake specific energy consumption *vs.* load

Since the specific fuel consumption is not a reliable parameter to compare the different fuels having different calorific values, density and viscosity rather than the brake specific energy consumption in which the fuel consumption rate and calorific values are taken in to account [19]. Figure 6 shows the effect of load on specific energy consumption for different fuels. The specific energy consumption is higher at part load conditions invariably for all the fuels and it tends to decrease with increasing load. Higher specific energy consumption is an indication of efficiency reduction. The specific energy consumption for mixed fuel mode is higher than the single fuel mode for all load conditions. The brake specific energy consumption of fossil diesel (FD), fossil diesel + producer gas (PG), biodiesel (BD), and biodiesel + producer gas are 12.63, 13.22, 12.03, and 13.45 MJ/kWh, respectively at full load conditions. The engine power derating trend represents the inefficient energy conversion from the fuel to useful work due to the inert gases present in the producer gas and its slow burning nature [20].

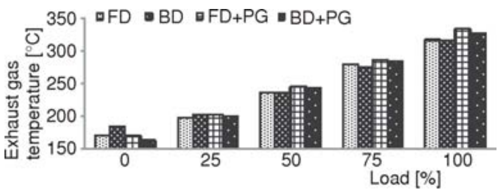

Figure 7. Exhaust gas temperature *vs.* load

Emission characteristics

Figure 7 shows the variation of exhaust gas temperature with load. Exhaust gas temperature with fossil diesel + producer gas fuel mode is higher than the biodiesel + producer gas. In general exhaust gas temperature during mixed fuel mode is higher than the single fuel mode and this might be the indication of excess energy supplied to the engine [21].

Low exhaust gas temperature with biodiesel is mainly due to the early start of combustion, which permits more time and crank angle for the expansion process and recover energy from combusted products [22]. Shorter ignition delay and lower calorific value of biodiesel also play a vital role. These results are similar with other references [16, 17, 23, 24]. Higher exhaust gas temperature is an indication of NO_x formation [18].

Emission of CO is an indication of incomplete combustion [25, 26]. Figure 8 shows the effect of load on CO emission level. The CO emission for mixed fuel mode operation is always much higher than the single fuel mode. In the single fuel mode biodiesel blends emits slightly higher CO emission and it increases with increasing load. Biodiesel blend required more time to evaporate than the fossil diesel which is evident from the evaporation study could be the reason behind the issue. Contrarily in mixed fuel mode biodiesel + producer gas combination emits lower CO emission than the fossil diesel + producer gas combination and the trend of emission level decreases with increasing load. The supply of producer gas reduces the fresh air intake through the inlet manifold which in turn reduces the oxygen to meet out the combustion process successfully and leads to increase CO concentration. In addition to that, the lower heating value of producer gas and biodiesel and lower adiabatic flame temperature of producer gas also have its own impact [21].

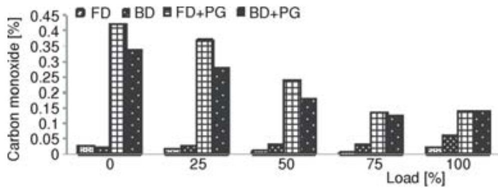

Figure 8. Carbon monoxide *vs.* load

The CO_2 emission in the case of mixed fuel mode operation for compression ignition (CI) engine is not considered since the carbon in the biodiesel and producer gas is a part of global carbon cycle and hence, it does not contribute to global warming [4].

Unburnt HC emission is also the indication of incomplete combustion which is shown in fig. 9. It represents that there is a unique trend of increase in HC emissions with corresponding increase in load for all mode of operations. The HC emission for fossil diesel and biodiesel in mixed fuel at full load is about 16.9 and 8.62% higher than the corresponding single fuel mode operation mainly due to the lower calorific value and inert gas presence in the producer gas. Reduction of HC emission with biodiesel is about 18.30% than the fossil diesel fuel mode. This emission reduction with bio-fuel is not only by the presence of oxygen but also by the cetane number.

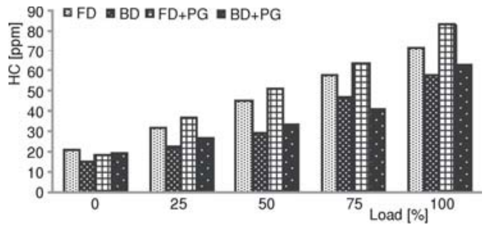

Figure 9. Hydrocarbon *vs.* load

The NO_x emission is correlated with maximum temperature in the cycle, equivalence ratio, percentage of load applied and amount of oxygen concentration in the combustion chamber [25]. Figure 10 shows the effect of load on NO_x emission for both single fuel and mixed fuel mode of operations. The NO_x emission for single fuel mode is much lower than the mixed fuel mode since the producer gas has no organic nitrogen [21]. It is evident that the maximum NO_x is 572, 534, 710, and 611 ppm for corresponding fossil diesel, biodiesel, fossil diesel + producer gas, and biodiesel + producer gas fuel mode of operations. It is also observed that NO_x emissions increase with increase in load for all modes of operations. This NO_x emission can be reduced by using suitable exhaust gas re-circulation technique and by employing catalytic converters.

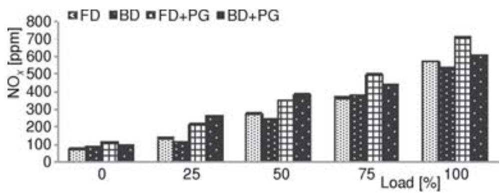

Figure 10. Nitrogen oxides *vs.* load

Figure 11 shows the effect of load on smoke opacity. 19.82 and 9.33% of smoke opacity reduction is observed with fossil diesel and

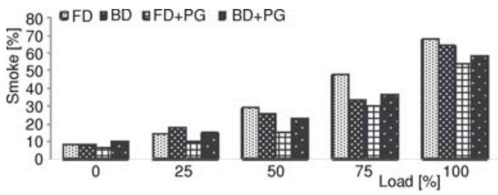

Figure 11. Smoke opacity *vs.* load

biodiesel in mixed fuel mode operation than the single fuel mode. Higher smoke opacity is observed with fossil diesel followed by biodiesel, biodiesel + producer gas and fossil diesel + producer gas. At full load the smoke opacity is 67.6, 64.3, 54.2, and 58.3% for corresponding fossil diesel, biodiesel, fossil diesel + producer gas, and biodiesel + producer gas mode operations. Higher cetane number of biodiesel tends to reduce the smoke opacity than the fossil diesel fuel operation [27]. However the smoke opacity increases with load for all modes of fuel operations and represents poor atomization characteristics particularly at higher load conditions. The same trend is observed with many reported studies [15, 26]. As the engine is running at constant speed, the time for complete combustion is reduced with increasing load which leads to increase the smoke opacity. Since the engine is a quality governing engine, the fuel supply increases to the corresponding increase in load. In general higher order of smoke opacity is observed with this agricultural open combustion chamber engine for all load and all fuel modes than the automotive engines.

Conclusions

The evaporation rate of neat used vegetable oil methyl ester and B23 blend has been measured under slow convective environment of air flowing with a constant temperature. Evaporation constants have been determined by using the droplet regression rate data. The experimental results in general agree with the d^2 law, the standard model that describes the droplet vaporization. On other side, the brake thermal efficiency of fossil diesel + producer gas and biodiesel + producer gas are 27.23 and 26.77%, respectively, which is 4.49 and 10.59% less than the corresponding single fuel mode operations at full load. Lower brake specific energy consumption is observed with single fuel mode than the mixed fuel mode. Reduction in HC emission with biodiesel in single fuel mode as well as in mixed fuel mode is observed. Smoke opacity with biodiesel in single fuel mode is 29% less and in mixed fuel mode is 23% less than the fossil diesel operation.

Nomenclature

B0 – neat fossil diesel
B20 – 20% biodiesel + 80% fossil diesel
B23 – 23% biodiesel + 77% fossil diesel
B40 – 40% biodiesel + 60% fossil diesel
B60 – 60% biodiesel + 40% fossil diesel
B80 – 80% biodiesel + 20% fossil diesel
B100 – neat biodiesel
BD – biodiesel
bTDC – before top dead centre
d – diameter of the droplet, [m]
FD – fossil diesel
K – evaporation rate constant
PG – producer gas
SS – stainless steel
t – droplet time, [s]
t_d – droplet evaporation life time, [s]
VCR – variable compression ratio

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Paper submitted: June 4, 2013
Paper revised: February 12, 2014
Paper accepted: April 20, 2015