Combustion Behavior of Bioethanol Fumigated DI Diesel Engine

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Abstract: In this study, bioethanol produced from madhuca indica flower is used as an alternative fuel for compression ignition (CI) engines. Four different flow rates of bioethanol viz. 0.24, 0.48, 0.96 and 1.22 kg/h is fumigated with the help of a vaporiser which comprises an electric heater and an electronically controlled injector. The test engine used in this in-vestigation is a single cylinder, four stroke, air cooled, direct injection (DI) diesel engine with a rated power of 4.4 kW at 1500 rpm. The combustion parameters of the diesel engine run on bioethanol fumigation were evaluated, analysed, compared with diesel operation and presented in this paper.

Keywords: *Bioethanol, Combustion, Diesel Engine, Fumigation.*

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I. Introduction

Biofuels such as bioethanol and biodiesel are of great interest today as their energy secu-rity and renewable nature. Bioethanol has the capability to reduce the greenhouse gas emissions and also it can reduce the NOx and smoke simultaneously in diesel engine. It can be obtained from simple sugar such as sugar cane, sugar beet, molasses, or from other carbohydrates that can be converted to sugar, such as starch and cellulose. The starchy feed stocks are corn, maize, potatoes etc. and cellulosic material are such as wood, forest residue, agricultural residue, crop residue etc [1].

Bioethanol can be used with diesel by adopting methods such as blending or solution, emulsion, fumigation, dual injection, spark ignition or surface ignition, by adding ignition improvers [2]. It is reported that upto 50% of the total fuel energy at full load can be pro- vided through ethanol fumigation, which lies between the energy substitutions achievable by blends (25%) and dual injection (90%) [3]. Research works have been documented with the fumigation of gaseous and light fuel like hydrogen, methane, propane, acetylene, methanol, gasoline [4-7]. With ethanol fumigation, the particulate matter size was found to half with higher substitution of ethanol fumigation compared to that of ethanol diesel blends, at full load [8]. It was also reported that by fumigating ethanol and methanol in amounts up to 55% of the total fuel energy, the ignition delay and CO was found to be increased and NO and thermal efficiency was found to be dropped at heavy loads [9]. Also to reduce the HC and CO emission, a diesel oxidation catalyst was used in a 4-cylinder Ford 2701C engine [10]. Chauhan et al. [11] was reported that, the performance was im-proved, and the NO and smoke emissions were found to be reduced with the 15% of etha-nol fumigation. Bioethanol was introduced in the intake manifold of the engine using a carburettor and its quantity was controlled by a butterfly valve according to the variation of loads [11]. The combustion analysis was done on a modern turbo-charged inline 6-cylinder Cummins diesel engine (ISBe220 31) with a common rail injection system at 2000 rpm and results indicated that, at the 40% substitution of ethanol, the ignition delay began to decrease which may be due to early ignition of the fumigated ethanol. A conclu-sion was made that there was an increase in the inter-cycle variability with the high substi-tutions of ethanol [12].

The present research work is aimed to establish madhuca indica flower as a feed stock for bioethanol production. The research work is also aimed to investigate the combustion, per-formance and emission of a single cylinder, four stroke, DI diesel engine running on a dual fuel mode using bioethanol fumigation.

II.Experimental Methods

A. Feedstock

The feedstock madhuca indica flower was collected from the madhuca indica tree for the investigation. It is a forest tree grown abundantly in the tropical regions of Asia and Aus-tralia. The residues from the tree are used for different purposes, such as cattle feed and biomass used in direct combustion. The annual production of madhuca indica flowers in India in the year 2006 was estimated to be approximately 48000 M Tonnes [13-14]. The fresh madhuca indica flowers can be used as a source of bioethanol production. The tribal people from different locations in India and Pakistan produce country liquor by the fer-mentation process. Sujit kumar Mohanty et al. [13] established the production method for bioethanol from the madhuca indica flowers by solid state fermentation. They also studied various factors, such as the moisture content, initial pH and temperature, affecting bioetha-nol production. Fig. 1 illustrates the schematic diagram of bioethanol production process. Bioethanol is produced from madhuca indica flowers by the fermentation process, using saccharomyces cerevisiae. The fresh flowers of madhuca indica were collected from the village people, cleaned properly to remove the adhering soil particles, and dried in the

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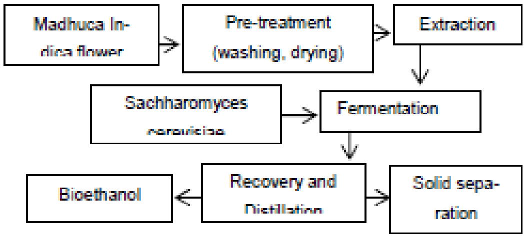


Figure 1. Production process of bioethanol from feed stock.

The yeast (Saccharomyces cerevisiae) was cultured on YENB (Yeast Extract Nutrient Broth) having 5% glucose and 1% of yeast extract for 48 hours. The madhuca indica flow-ers were pre-treated for the extraction of sugars. The flowers of madhuca indica and dis-tilled water in a 2:1 ratio were auto-claved, at a pressure of 10 lb/inch2 for 15 minutes. For the fermentation process, a starter culture was added at the rate of 10% (v/v) to the mad-huca indica extract taken in a 1000 ml Erlenmeyer flask, and fermentation was carried out in a batch on laboratory bench at a temperature of 30ºC ± 2 °C for 96 hours. After the fer-mentation process, the first distillation was done to get the crude extract and further, frac-tional distil-lation was done for the removal of water. The purity of bio-ethanol was checked by an alcoholmeter.

B. Fuel properties

The physical properties of bioethanol produced from the madhuca indica flower were tested in a standard fuel testing laboratory, i.e., ITA lab, Kolkata. The properties of bio-ethanol from madhuca indica flower and diesel are compared and given in TABLE I

Properties	**Diesel**	**Bioethanol from madhuca indica flower**
Density (kg/m^3)	870	800
Lower heating value (MJ/kg)	42.8	29.4
Cetane number	50-55	5-15
Kinematic viscosity	2.58	1.73
Auto-ignition temperature (^{o}C)	210	329

table 1. comparison of properties of bioethanol and diesel

C. Test engine

The test engine used for the experiment was a single cylinder, four-stroke, and air cooled, DI diesel engine with the maxi-mum rated power of 4.4 kW, at a constant speed (1500 rpm). Fig. 2 illustrates the general schematic diagram of the experi-mental set up, and the technical specifications of the engine are given in TABLE II. In this investigation, diesel was stored in a fuel tank and an automatic solenoid controlled type bu-rette was used for the fuel consumption readings. To accumu-late sufficient air, an air box was fitted with the engine intake manifold.

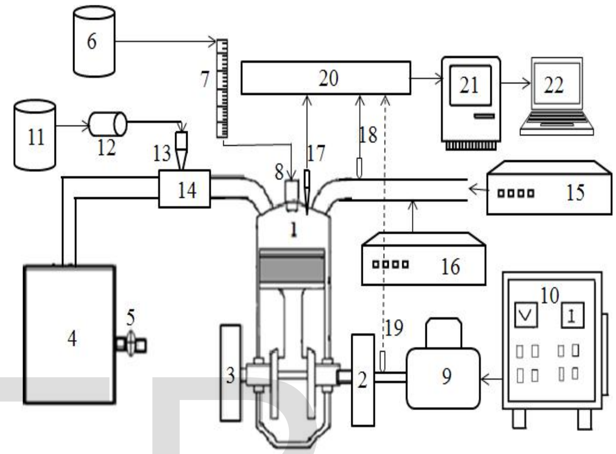


Figure 2. Schematic diagram of experimental set up.

1.Engine	9. AC generator	16.AVL Digas 444 analyser
2.Flywheel	10.Load bank	17.Pressure trans-ducer
3.Crankshaft	11.Fuel tank for Bio-ethanol	18.Exhaust gas sensor
4.Air box	12.Fuel pump	19.Speed sensor
5.Manometer	13.Electronically controlled injector	20.Control panel board
6.Fuel tank for Diesel		21.Data acquisi-tion system
7.Burette	14.Vaporiser	22.Computer
8.Injector	15.AVL 437 C smoke meter	

A manometer fitted in the air box showed the reading of the water head, which was used to calculate the air consumption of the engine. The fumigation was done with the help of a fuel tank, electronically controlled injector, fuel pump and vapor-iser. The arrangement used in this study for the fumigation of bioethanol is shown in Fig. 3. A 12 V, 5 nozzles, solenoid based electronic fuel injector of 300 kPa injection pressure was connected to the intake manifold of a diesel engine. Bioethanol stored in a tank was pumped using a 12 V fuel supply pump and supplied to the fuel injector. One of the output pins of a microcon-troller (Atmega-328) was connected to the injector through a motor driver (L293D).

Table 2. Technical specifications of diesel engine

Type	Kirloskar TAF1 Vertical diesel engine
No. of cylinder	1
Type of injection	Direct
Rated power at 1500 rpm, kW	4.41
Bore, mm	87.5
Stroke, mm	110
Compression ratio	17.5
Method of cooling	Air cooled with radial fin
Displacement volume, litres	0.662
Fuel injection timing BTDC, de-gree	23°
Number of injector nozzle holes	3
Nozzle-hole diameter, mm	0.25

$$\frac{\partial E}{\partial \theta} = \vartheta \frac{\partial P}{\partial \theta}(1/\gamma - 1) + P\frac{\partial \theta}{\partial \theta}(\gamma/\gamma - 1) + \frac{\partial E_W}{\partial \theta} \quad ....(1)$$

The microcontroller works at 5 V and the injector works at 12 V with high current; L293D was used to provide proper cur-rent and voltage to the injector. The microcontrol-ler was pro-grammed to generate a PWM (pulse width modulation), to control the quantity of bioethanol to be injected. The PWM is basically a duty cycle, which delivers bioetha-nol in different quantities.

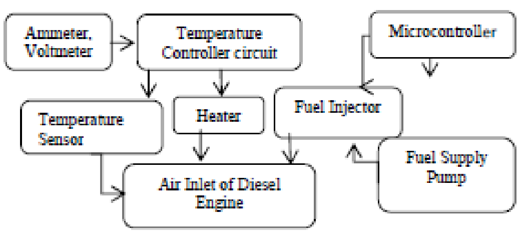


Figure 3. Ray Diagram of Fumigation technique.

Bioethanol was injected continuously at regular intervals. Four different flow rates, viz., 0.24. 0.48, 096 and 1.22 kg/h were used in this investigation. The fuel injector was at-tached to an electric heater whose temperature was maintained at 70 °C. A K-type ther-mocouple based temperature sensor was used to measure the reading, and an automatic cut-off circuit main-tains the heater temperature at the required level. An AVL444 Digas analyser was used to measure the HC, CO, NO emis-sions in the exhaust. The gas analyser was inserted and kept in the exhaust pipe for a few minutes to measure the emissions. The HC and CO, CO2 emissions were measured with the help of the gas analyser that works on the NDIR principle. The NO emission was measured by the photochemical sensor. An AVL 437 C diesel smoke meter was used to measure the smoke density of the engine ex-haust. A K-type thermocouple with a temperature indicator was fitted in the exhaust pipe indicating the temperature of the exhaust gas. The data collected by the data acquisition system from all the sensors were displayed on the monitor of the computer. Initially, the engine was operated with diesel to obtain the reference data at different loads, ranging from 0 to 100% for 1 hour to complete one set of measurement. Further, the experiments were conducted with bioethanol fumigation at different loads. As bioethanol was supplied at four different flow rates, the total energy supplied to the engine was not fixed, and also the global equivalence ratio would change for the different flow rates.

III. Results and discussion

A. Pressure-crank angle history

The pressure crank angle history for diesel and the bioethanol fumigation at 0.24, 0.48, 0.96 and 1.22 kg/h, at full load of the engine, are depicted in Fig. 4. The pressure crank angle history gives a gross indication of the performance and knocking con-dition of the engine.

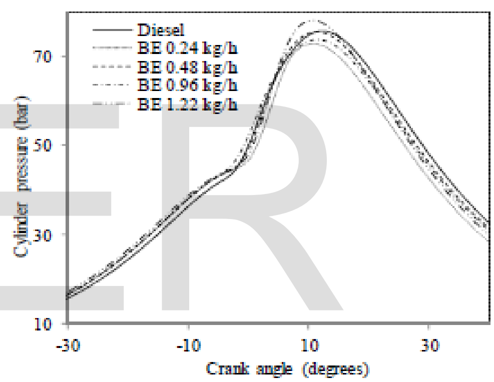


Figure 4. Pressure crank angle diagram at full load.

It is depicted from the figure that, the peak cylinder pressure of 1.22 kg/h bioethanol fu-migation is found to be the highest, compared to that of diesel and bioethanol at 0.24, 0.48 and 0.96 kg/h, at full load. The occurrence of the maximum cylinder pressure for diesel is approximately at 12.41 °CA aTDC, which is the earli est among the tested fuels in this study. For bioeth-anol fumigation, the occurrences of the maximum cylinder pressure at 0.24, 0.48, 0.96 and 1.22 kg/h are found to be ap-proximately at 10.71, 11.63, 11.31, 10.439 °CA aTDC, respec-tively at full load.

B. Maximum heat release rate

The heat release analysis can provide information about the effects of engine design changes, fuel injection system, fuel type, and engine operating conditions, on the combus-tion process and engine performance [15]. The heat release rate is calculated, using the first law analysis of thermodynamics.

The heat release rate at each crank angle was de-termined by the following formula:

where,

$\frac{dQ}{d\theta}$ = rate of heat release (J/°CA)

ϑ = gas volume (m^3)

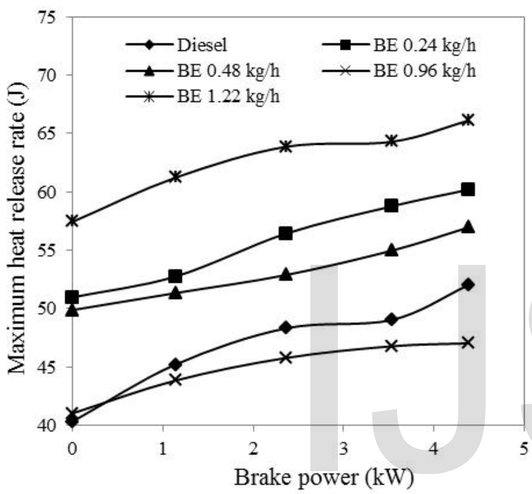
P=cylinder pressure (bar)

θ = crank angle (°)

γ = ratio of specific heat

$\frac{dQ_w}{d\theta}$ = rate of heat transfer from the wall (J/°CA)

Fig. 5 shows the variation in the maximum heat release rate with brake power for diesel and bioethanol fumigation at different flow rates.



The maximum heat release rate for diesel, at 0.24, 0.48, 0.96 and 1.22 kg/h flow rate of bioethanol is found to be about 51.84, 60.20, 56.96, 50.11 and 66.10 J/°CA, respectively, which is achieved at about 10.72, 7.14, 6.98, 6.67 and 7.45 °CA aTDC at full load. For bioethanol fumigation at 1.22 kg/h, the heat release rate is found to be higher than those of other flow rates, due to the availability of more oxygen and longer ignition delay which provide enhanced combustion.

C. Ignition delay

The variation of ignition delay with respect to brake power for diesel and 0.24, 0.48, 0.96 and 1.22 kg/h flow rate is shown in Fig. 6. The ignition delay is defined as the interval between the injection timing of diesel and the point of cycle at which the heat release changes from a negative value to zero value, and after that point it will have only positive values [16].

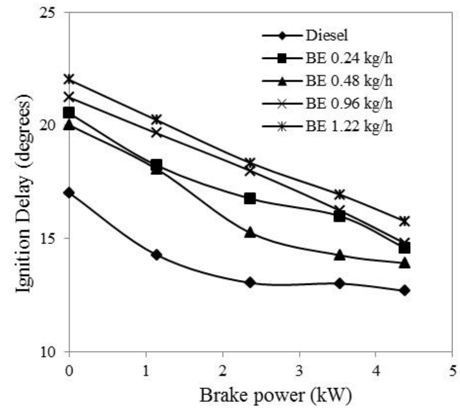


Figure 6. Variation of ignition delay with brake power

The ignition delay (τid) is a function of the mixture temperature, pressure, equivalence ratio, kinetics of the fuel oxidation at lower temperatures, mixture homogeneity and fuel properties. For bioethanol fumigation at 0.24, 0.48, 0.96 and 1.22 kg/h flow rates, the val-ues of ignition delay are about 14.57, 13.91, 14.78 and 15.76 °CA at full load. The ignition delay of all the tested fuels in this study decreases with an increase in the brake power, as a result of increased cylinder gas temperature. It is also apparent from the figure that for all the flow rates of bioethanol, the ignition delay is more compared to that of diesel due to low Cetane number and large latent heat of vaporisation of bioethanol.

D. Combustion duration

The combustion duration is the duration measured in the crank angle between 10% mass burned and 90% mass burned. Fig. 7 depicts the variation in the combustion duration of diesel, and the fumigation of four different bioethanol flow rates viz. 0.24, 0.48, 0.96 and 1.22 kg/h, respectively with brake power. The combustion duration increases from mini-mum brake power to maximum brake power with the increase of the fuel quantity. At full load, the value of combustion duration for diesel, 0.24, 0.48, 0.96 and 1.22 kg/h of fumi-gated bioethanol is found to be 38.37, 30.94, 37.84, 38.29 and 34.01 °CA, respectively. At 1.22 kg/h flow rate, the combustion duration is shorter due to the accumulation of higher amount of bioethanol gives a rapid combustion. More oxygen is available in this flow rate.

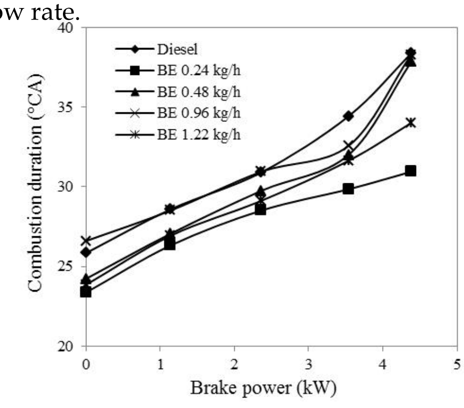


Figure 7. Variation of combustion duration with brake power.

The rate of pressure rise is the derivative of pressure (dP/dθ) with respect to crank angle, which indicates how rapidly the pressure changes and impacts on the engine combustion chamber, piston head etc. The maximum rate of pressure rise should not exceed 8 bar/°CA to increase the life and reduce the noisy operation of engine [17]. Also at lower flow rate i.e. at 0.24 kg/h flow rate, the combustion duration is shorter, as the bioethanol is vapor-ised at 70 °C, it mixes with air rapidly to form ho mogeneous mixture in premixed combus-tion phase hence combustion is faster.

E. Maximum rate of pressure rise

Fig. 8 presents the variation in the maximum rate of pressure rise with brake power for diesel and fumigated bioethanol at 0.24, 0.48, 0.96 and 1.22 kg/h, respectively at full load.

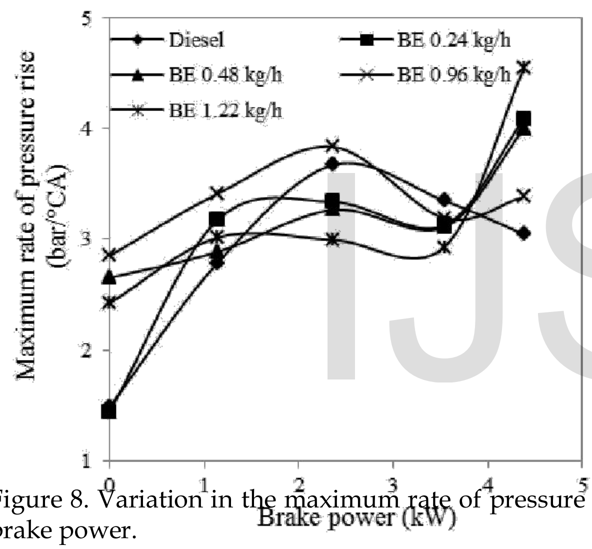


Figure 8. Variation in the maximum rate of pressure rise with brake power.

The maximum rate of pressure rise for diesel and bioethanol fumigation at 0.24, 0.48, 0.96 and 1.22 kg/h is found to be about 3.68, 4.08, 4.01, 3.38 and 4.54 bar/°CA respectively, which is achieved approximately at about 2.25, 4.16, 3.48, 2.03 and 3.87 °CA aTDC re-spectively, at full load. From the figure, it is also inferred that the bioethanol fumigation at a flow rate of 1.22 kg/h gives the highest maximum rate of pressure rise compared to die-sel and other flow rates of bioethanol. This results in the noisy operation during the en-gine's running condition, as a result of longer ignition delay.

F. Mass fraction burned

Fig. 9 depicts the variation in the MFB with the crank angle at full load. The energy con-version during a combustion cycle can be described by the mass fraction burned (MFB) at a spe-cific crank angle degree (CAD). In a CI engine, the MFB de-pends on the engine ge-ometry, engine speed, F/A, ignition angle, residual mass etc. The MFB in each individual engine cycle is a normalized quantity with a scale of 0 to 1, describing the process of chemical energy release as a function of the crank angle. The MFB includes the determina-tion of the start and end of combustion [18]. One well-established method is the one de-veloped by Rassweiler and Withrow, for estimating the mass fraction burned profile from the cylinder pressure and volume data. In this method, the mass fraction burned is given by the empirical relation;

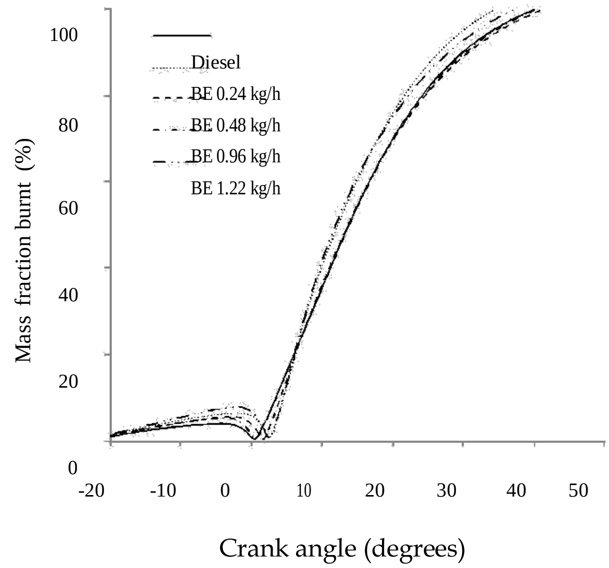


Figure 9. Variation in the mass fraction burned with crank angle at full load.

where,

0-denotes the start of combustion,
N – end of combustion (N is the total number of cra nk inter-vals).
ΔPc – pressure rise due to combustion
i- integer crank angle location

It is apparent from the figure that, the combustion starts earli-er for diesel after the delay period, but the combustion of 0.24 and 1.22 kg/h is faster after 5.66 °CA aTDC. The com-bustion of 0.48 and 0.96 kg/h flow rate is closer to that of diesel. The expected end of combustion for diesel, and bioethanol fumiga-tion at 0.24, 0.48, 0.96 and 1.22 kg/h flow rates, is found to be about 40.06, 34.51, 41.29, 40.32 and 37.28 °CA aTDC, respec-tively. With the bioethanol fumigation of 0.24 kg/h flow rate, the vaporisation and atomisation of fuel is better due to the preheated air, and at 1.22 kg/h flow rate the higher admission

$$MFB = \frac{m_b(i)}{m_b(total)} = \frac{\sum_{0}^{i} \Delta P_c}{\sum_{0}^{N} \Delta P_c} \qquad \text{------------------- (2)}$$

of bioethanol increases the oxygen content of air, and there-fore, the mass fraction burnt is high.

IV. Conclusion

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The conclusions of the results obtained from the combustion parameters of a single cylin-der, four stroke, air cooled , DI diesel engine, running with diesel as injected fuel and bio-ethanol fumigated at four different flow rates, viz., 0.24, 0.48, 0.96 and 1.22 kg/h are as follows;

- The peak cylinder pressure for diesel occurs at 12.41 °aTDC, whereas for 0.24, 0.48, 0.96 and 1.22 kg/h bioethanol flow rates it occurs at 10.71, 11.63, 11.31, 10.439 °aTDC, respec-tively.

- The maximum rate of pressure rise for diesel, 0.24, 0.48, 0.96 and 1.22 kg/h flow rate of bioethanol is found to be 3.68, 4.08, 4.01, 3.38 and 4.54 bar/°CA respectively, which is achieved at 2.25, 4.16, 3.48, 2.03 and 3.87 °CA aTDC respective-ly, at full load.

- At full load, the value of combustion duration for die-sel, 0.24, 0.48, 0.96 and 1.22 kg/h of fumigated bioethanol is found to be 38.37, 30.94, 37.84, 38.29 and 34.01 °CA, re-spectively.

- The expected end of combustion for diesel, 0.24, 0.48, 0.96 and 1.22 kg/h of fumigated bioethanol is found to be 40.06, 34.51, 41.29, 40.32 and 37.28 °CA aTDC, respec-tively.

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