INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX

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Effect of pilot fuel injection pressure and injection timing on combustion, performance and emission of hydrogen-biodiesel dual fuel engine

Mukund Kumar [a], *Subrata Bhowmik* [b], *Abhishek Paul* [a,*]

[a] Department of Mechanical Engineering, NIT Silchar, India
[b] Department of Mechanical Engineering, IIT (ISM) Dhanbad, India

HIGHLIGHTS

- Higher pilot injection pressure and injection advancement improves hydrogen combustion.
- Pilot injection angle retardation reduces NOx emission.
- UHC, CO and soot emissions are improved with higher FIP and advanced FIT.
- Premixed combustion improved with pilot injection advancement.

ARTICLE INFO

Article history:
Received 19 September 2021
Received in revised form
31 May 2022
Accepted 26 June 2022
Available online xxx

Keywords:
Dual fuel diesel engine
Jatropha biodiesel
Hydrogen fuel
Fuel injection pressure
Fuel injection timing

ABSTRACT

The present study highlights the influence of fuel injection pressure (FIP) and fuel injection timing (FIT) of Jatropha biodiesel as pilot fuel on the performance, combustion and emission of a hydrogen dual fuel engine. The hydrogen flow rates used in this study are 5lit/min, 7lit/min, and 9lit/min. The pilot fuel is injected at three FIPs (500, 1000, and 1500 bar) and at three FITs (5°, 11°, and 17bTDC). The results showed an increase in brake thermal efficiency (B_{th})from 25.02% for base diesel operation to 32.15% for hydrogen-biodiesel dual fuel operation with 9lit/min flow rate at a FIP of 1500 bar and a FITof17bTDC. The cylinder pressure and heat release rate (HRR) are also found to be higher for higher FIPs. Advancement in FIT is found to promote superior HRR for hydrogen dual fuel operations. The unburned hydrocarbon (UHC) and soot emissions are found to reduce by 59.52% and 46.15%, respectively, for hydrogen dual fuel operation with 9lit/min flow rate at a FIP of 1500 bar and a FIT of 11bTDC. However, it is also observed that the oxides of nitrogen (NO_X) emissions are increased by 20.61% with 9lit/min hydrogen flow rate at a FIP of 1500 bar and a FIT of 17bTDC. Thus, this study has shown the potential of higher FIP and FIT in improving the performance, combustion and emission of a hydrogen dual fuel engine with Jatropha biodiesel as pilot fuel.

* *Corresponding author.*
E-mail address: v1.abhishek@gmail.com (A. Paul).

https://doi.org/10.1016/j.ijhydene.2022.06.260

Please cite this article as: Kumar M et al., Effect of pilot fuel injection pressure and injection timing on combustion, performance and emission of hydrogen-biodiesel dual fuel engine, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.06.260

Nomenclature

BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
bTDC	Before top dead centre
B_{th}	Brake thermal efficiency
CI	Compression ignition
CO	Carbon mono dioxide
CO_2	Carbon dioxide
CRDI	Common rail direct injection
DAQ	Data acquisition
FFA	Free fatty acid
FIP	Fuel injection pressure
FIT	Fuel injection timing
HRR	Heat release rate
NO_X	Oxides of nitrogen
UHC	Unburned hydrocarbon
HES	Hydrogen energy share

Introduction

Modernization and urbanization of human civilization in recent decades have increased the usage of vehicles and this has caused a severe demand for fossil fuels [1]. Among IC engines, diesel engines or compression ignition engines have a wide application in various sectors of our modern world, which includes industry, road transport, agriculture, construction, and small electric power production because of their convenient features, such as high performance, lesser fuel consumption, reliability, durability, simplicity of operation, adaptability and low cost [2–4]. However, the excessive emissions of NO_X and particulate matter have gradually truncated the usage of Diesel engines over the years, as there has been a significant increase in global consciousness against the environmental pollution [5]. In order to curtail the emissions from the engines and to reduce dependency on fossil fuel, there has been a lot of research on usability of non-conventional and renewable fuel sources [6] such as biodiesel [7–9], liquefied petroleum gas (LPG) [10–12], hydrogen [13–15], and compressed natural gas (CNG) [16,17].

Based on the accessibility and wide production potentialities, biodiesel is considered to be one of the most suitable alternatives to diesel fuel [18]. Biodiesel is a commercial name given to mono-alkyl esters of long chain fatty acid as its properties closely resemble to that of petroleum Diesel [19]. However, there is a fine line of difference between biodiesel and Diesel as the former comprises of saturated and unsaturated mono alkyl esters, whereas, the latter is a complex mixture of thousands of hydrocarbons of different chain length, mostly saturated [20]. Biodiesel can be produced from a variety of feedstock through an acidic or basic catalysed transesterification process. Among the various feedstock investigated, *Jatropha curcas* has a very high oil yield that ranges between 38.7% and 45.8% [21]. Jatropha oil also has a very high biodiesel yield of above 97% with acidic pre-treatment and base catalysed transesterification [22]. Jatropha biodiesel has a high cetane content of 51 (ISO 5165) [23], calorific value of 39.42 kJ/kg [24], oxygen content of 10.8% (by wt%) [25]. Jatropha biodiesel can produce almost equal power as compared to diesel, with a slightly drop in thermal efficiency [26]. It also produces lesser UHC, CO and soot emissions as compared to diesel [27]. However, the NO_X emissions of the engine increase a little with Jatropha biodiesel [28]. Hence, the Jatropha biodiesel is considered as a viable option for a trial or complete replacement of petroleum Diesel. *Namasivayam* et al. [29] studied Rapeseed methyl ester as pilot fuel with natural gas fuelled diesel engine. They observed a substantial increase in B_{th} and NO_X emissions. They also found a diverse reduction in UHC and CO emission. *Selim* et al. [30] used Jojoba methyl ester as pilot fuel with liquefied natural gas as main fuel in dual fuel operation. They observed an improvement in performance, reduction in combustion noise, and reduction in cyclic combustion variability. *Banapurmath and Tewari* [31] used Honge methyl ester as pilot fuel with produced gas in dual fuel operation. They observed reduction in B_{th} and NO_X emissions with rise in UHC and CO emission. *Korakianitis* et al. [32] have examined rapeseed methyl ester as pilot fuel along with hydrogen and natural gas in dual fuel set up. They observed NO_X emissions rises with hydrogen, while UHC emission rises with natural gas. *Namasivayam* et al. [33] have studied separately with Rapeseed methyl ester and natural gas in dual fuel mode. They reported lower emissions of smoke and NO_X emissions, whereas a higher CO and UHC emission was also witnessed. *Yoon and Lee* [34] conducted an experiment to investigate the effect of biogas–biodiesel approach on the combustion and emission characteristics in dual-fuel mode. They noticed lower NO_X emissions with greater improvement in performance along with decrease in soot emission. *Ryu* et al. [35] studied with biodiesel–CNG in dual fuel mode. They noticed a significant decrement in NO_X emissions. They also noticed as biodiesel has lower calorific values than Diesel, which upsurges the BSFC of the engine.

Over the years, research on duel fuel combustion in CI engine has come up a long way. There has been an appreciable amount of research done towards effective e utilization of gaseous fuels in CI engine architecture. The primary motivation behind the development of dual fuel engine technology is to increase the homogeneous nature of the charge inside the combustion chamber so that the premix phase of the combustion can be extended [36]. This not only provides higher efficiency of the engine but also significantly reduces the emissions. In recent years, hydrogen is also considered as an effective energy resource for IC engines, because of its properties, such as high calorific value, higher ignitibility, smaller quenching gap, higher burning velocity have made it extremely suitable for engine applications [37,38]. The hydrogen combustion in a CI engine has the potential to reduce the heterogeneity of the air-fuel mixture, which produces higher diffusion of hydrogen and results in increased flammability of the charge [39]. The hydrogen is a non-toxic, odourless, carbon free renewable source of energy that produces only water during combustion. As a result, the engine application of hydrogen reduces the emission of UHC and oxides of Carbon emissions [40–43]. All these favourable features of hydrogen have constructed a suitable path for its

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utilizing in CI engine under dual fuel mode. Several studies performed previously to analyse the effect of gaseous fuels on engine combustion, performance and exhaust emissions under dual fuel mode. *Baltacioglu* et al. [44] analysed the effects of clean hydrogen and HHO with biodiesel on engine performance and exhaust emission and reported that the performance improvement with increased HHO share is higher than clean hydrogen, although the later gave better emissions than HHO. *Yaliwalet al*. [45] studied the impact of hydrogen enriched producer gas on the engine characteristics of CI engine with pilot diesel and Honge biodiesel (HOME). The findings revealed that increase in Hydrogen energy share (HES) to PG substantially influence the combustion and emission parameters. It was also seen that HOME-PG combination improved performance with 4 lit/min, 8 lit/min and 12 lit/min of hydrogen share compared to base diesel operation. *Khandal* et al. [46] experimentally investigated the effect of flow rate of hydrogen with honge biodiesel and cotton seed biodiesel on engine performance, emissions and combustion of a dual fuel engine. The study reported a decrease in B_{th} using Hong and cottonseed oil biodiesel as pilot fuel for higher hydrogen dual fuel operations. Hence, it was reported that the hydrogen addition in lower proportions can improve the performance and exhaust emissions of the engine; however, the same may deteriorate slightly using biodiesel as a pilot fuel. *Li* et al. [47] analysed the effect of hydrogen/Natural Gas (NG) addition with varying engine load on the combustion and performance parameters of a diesel engine under dual fuel mode. It was observed in this study that hydrogen addition at high load substantially increases the het release rate of the diffusion combustion as compared to natural gas dual fuel operation. They also observed that hydrogen as well as natural gas share relatively at large fraction from medium (50% load or above) to high load improved the B_{th} while the same decreased at low load. *Tarabet* et al. [48] investigated the effect of hydrogen/NG ratio on the engine parameters of the engine under dual fuel mode using eucalyptus oil biodiesel as pilot fuel. It was found that NG enriched with hydrogen causes a substantial raise in HRR and cylinder pressure. Results also confirmed that, from low to moderate loads, BSFC was much higher and decrement in B_{th} was also observed under dual fuel mode. However, NG enriched hydrogen blends showed improvement in performance than pure NG especially for moderate to high loads. *Karagoz* et al. [49] observed that, with increasing hydrogen share with intake air slightly decreased the B_{th}. The Cylinder pressure increased by 7.81% and 36.20% with 22% and 53% hydrogen share respectively while the HRR also increased by 25.77% and 110.94% respectively. A great improvement in smoke emission level was also observed. *Tayari and Abedi* [50] investigated with microalgae with the hydrogen share of 0–10 lit/min for possible improvement in engine performance and exhaust emissions. It was observed that hydrogen dual fuel operations trigger an improvement in emissions of UHC and CO as compared to base diesel operation. It was further reported that with 10 lit/min of hydrogen supply, the improvement in BSFC, engine power and output torque was by 6.6%, 7.6%, and 10.6%, respectively. *Rocha* et al. [51] conducted an experiment on CI engine with the continuous supply of hydrogen and measured its effects on engine performance and exhaust emissions. Hydrogen was injected in concentrations of 2%, 6%, 8% and 10% of the entire fuel supply biodiesel/diesel (B7) along with hydrogen, which signifies energy ratios of 5%, 15%, 20% and 24% of total energy supply. The results indicated a reduction in BSFC with the increase of hydrogen supply. Similarly, UHC, CO and CO_2 emissions lessened with increment in hydrogen concentration. However, the NO_X emissions increased with Hydrogen addition. It was also observed an increase in the cylinder pressure and HRR because of reduction in ignition delay caused by maximum participation of hydrogen content. Hence it can be seen that the hydrogen addition can improve the performance and exhaust emissions of the engine, however, the same may deteriorate slightly using biodiesel as a pilot fuel. *Serin and Yıldızhan* [52] studied the influences of hydrogen addition to base diesel and blends with tea seed based biodiesel (B10 and B20) on conventional CI engine. The hydrogen energy share was varied from 0% to 20%. The study observed higher NO_X emissions while CO, CO_2 emissions reduced along with a substantial decrease in BSEC with 10% and 20% supplementation of tea seed biodiesel.

From the study of literature on dual fuel operations with different gaseous fuels and liquid pilot fuels, it is clearly understood that the mixing of liquid and gaseous fuels with air is a significant control parameter that can dictate the quality of the combustion. In case of conventional dual fuel injection system, the gaseous fuels are injected into the intake manifold during suction stroke and the liquid fuels are injected inside the combustion. Therefore, the gaseous fuels get sufficient time to produce homogeneous mixture with air. However, the liquid pilot fuels are injected much later stages of compression stroke and do not get sufficient time to mix with the gas-air mixture. So, the injection conditions of the pilot fuel dominate the dual fuel mixing process and control the combustion process. The study of relevant cited above shows that there is a lack of experimental works on the effect of pilot fuel injection parameters on the combustion, performance and emissions of a dual fuel engine. In case of biodiesel pilot operation, the experimental works are even sparse. Hence, the present work aims to investigate the effects of different liquid fuel injection timings and fuel injection pressures on the performance, combustion and emissions of a hydrogen dual fuel engine. In this study, pure biodiesel is used as pilot fuel at different injection angles and injection pressure is used to evaluate the variation of engine performance, combustion and emissions of a hydrogen dual fuel engine.

Experimental setup and methodology

Test fuels

The fuels used in this study are low sulphur diesel, hydrogen and Jatropha Biodiesel. The Diesel is collected from a local fuelling station, whereas the 99.99% pure hydrogen is collected in cylinders from local gas suppliers. The Jatropha biodiesel is prepared in the Fuel Research lab of NIT Silchar from raw Jatropha oil through base catalysed transesterification process. The free fatty acid (FFA) content of the oil is a very important parameter for determining the amount of catalyst for the transesterification process, as a higher amount of catalyst is required to counter the soap formation for oils with high FFA content. To this end, the FFA content of the Jatropha oil is calculated from its acid number, which is determined by the titration test. In this test, the acid number is calculated to be 0.215 mg KOH/g, which complies with the requirements of ASTM D 6751 and EN 14214 standards [53]. Therefore, the transesterification of the Jatropha oil is carried out with Methanol as the alcohol and Potassium Hydroxide (KOH) as the catalyst. The Methanol used here is 99.99% pure, whereas the KOH is 90% pure. The yield of the process is found to be 93.011%. Further, some of the vital properties of the produced biodiesel are measured and shown in Table 1.

Experimental setup and procedure

The present experimental work is conducted using a single-cylinder, four-stroke, water-cooled, CRDI diesel engine developing a rated power output of 3.6 kW at 1500 RPM available in the Advanced Engine Research Lab of NIT Silchar. The engine is connected to an air cooled eddy current dynamometer (Make: Powermag, Model:PM-5HP) and an 'S' type load cell (Make: Powermag, Model:CZL601). A crank angle encoder (Make: Kubler, Model: 8.5000.8352.0360) is attached to the crankshaft to measure the crank rotation. The pressure inside the combustion chamber is measured using a piezo-electric pressure transducer (Make:Cityzen, Model:P150EM). Several other combustion parameters, such as rate of heat release, ignition delay, etc. are calculated from the pressure datasets. The high cetane pilot fuel is injected in the combustion chamber through a solenoid injector (Make Bosch) using an ECU controlled high pressure CRDI system. The FIP and the FIT of the engine can be set to any desired value by means of the open ECU. The engine and calorimeter are cooled by a constant flow (70lit/hr) of water passing through them. The entire setup is shown in Fig. 1 and the vital specifications are shown in Table 2. The emissions of the engine are measured by an emission analyser (Make Testo, Model: 350). CO, CO_2, and UHC emissions are measured on the basis of Non-Dispersive-Infrared (NDIR) detection principle, while NO_X and $O_2$are measured by means of pre-calibrated electro-chemical sensors. The exhaust smoke is measured in terms of its opacity by means of a smoke opacimeter (Make: AVL, Model: 437C).

The hydrogen is injected into the intake manifold of the engine during the suction stroke by means of a dedicated gas injection system that is controlled by a separate open ECU system. The hydrogen gas stored at a pressure of 200 bar in a cylinder is routed through a pressure control valve, a flame arrester, a pressure gauge, a gas flow meter and finally a solenoid gas injector to inject it into the intake manifold of the engine. The injection of the gas is started 10°aTDC in the suction stroke and the injector is kept open throughout the injection stroke.

The engine experiments are conducted at three injections pressures, namely, 500 bar, 1000 bar and 1500 bar. Further, the injection timings are advanced by 5°, then 11° and finally 17bTDC. Before experimenting with dual fuel strategies, the engine is run on diesel to get a reference set of data in the above-mentioned operating conditions. This dataset is used as a benchmark while comparing the performance, combustion and emission characteristics of different biodiesel-hydrogen strategies. This was followed by biodiesel-hydrogen dual fuel operation with hydrogen flow rates of 5lit/min, 7lit/min, and 9lit/min. These strategies are named as 'B100H1', 'B100H2', and 'B100H3, respectively. The entire experimental matrix is shown in Table 3. All the experiments are carried out at full load condition. The engine is allowed to run for 15–20 min at each operating condition for each fuel sample to reach a steady-state condition. The ambient temperature and humidity of the lab are recorded to be 404 K and 81%, respectively.

Uncertainty analysis

All measurement of physical and functional parameters leads to some quantity of errors during operations. In this experimental study, the uncertainty is calculated using Eq. (1), [54]. The total percentage of uncertainty of the performance, and total sampling uncertainty and standard deviation of the exhaust emission parameters are tabulated in Tables 4 and 5, respectively.

$$\Delta U = \sqrt{\left(\frac{\partial U}{\partial x_1}\times \Delta x_1\right)^2 + \left(\frac{\partial U}{\partial x_2}\times \Delta x_2\right)^2 + \ldots + \left(\frac{\partial U}{\partial x_n}\times \Delta x_n\right)} \quad (1)$$

Where, ΔU = Total uncertainty of a definite quantity Q; Q = f [x_1, x_2, …,x_n]; Δx_1, Δx_2, …,Δx_n = Independent errors.

Results and discussion

Combustion characteristics

The combustion characteristics of the engine are evaluated on the basis of cylinder pressure and heat release rate.

Cylinder pressure

The cylinder pressure is a vital parameter to assess the combustion of an engine, as it directly affects the engine power output and exhaust emissions. The variation of combustion pressure is plotted against crank angle for the different tested FITs (5°, 11°, 17bTDC) and at different FIPS (500, 1000, 1500 bar) in Fig. 2 (A-L). It is primarily observed that the cylinder pressure tends to increase with increasing pilot fuel injection pressures, along with advancing pilot fuel injection timings and with increasing hydrogen participation. It can be seen from Fig. 2 (A-C) that the cylinder pressure for 5bTDC pilot injection is quite low for both base Diesel and biodiesel

Table 1 – Physico-chemical properties of Diesel, Jatropha biodiesel.

Property	ASTM method	Diesel	Jatropha biodiesel
Calorific value (kJ/kg)	D-4809	42,232	39,594
Density (kg/m^3)	D-4052	0.831	0.881
Kinematic viscosity @40 °C (mm^2/s)	D-445	3.21	4.12
Flash point (C)	D-93	76	162
Cetane number	D-976	47.14	48.13

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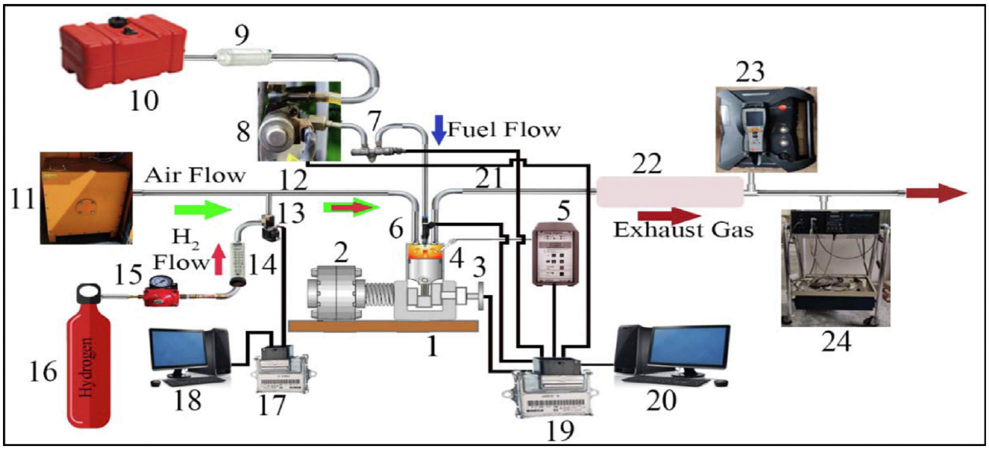

Fig. 1 – Experimental setup of hydrogen dual fuel engine. 1: Engine; 2: Eddy current dynamometer; 3: Crank angle encoder; 4: Pressure sensor; 5: Charge amplifier; 6: Liquid fuel injector; 7: Common rail; 8: High pressure pump; 9: Secondary fuel tank; 10: Main fuel tank; 11: Air box; 12: Intake manifold; 13: Gaseous fuel injector; 14: Gas flow meter; 15: Flame arrester; 16: Hydrogen cylinder; 17: Gas ECU; 18: DAQ; 19: CRDI ECU; 20: DAQ; 21: Exhaust manifold; 22: Calorimeter; 23: Emission analyser; 24: Smoke meter.

Table 2 – Specification of the test engine.

Make/Model	Kirloskar/AV 1
Type	Multi fuel
Cooling	Water
Bore/Stroke (mm)	80/110
Displacement (Swept Volume)	553 cc
Compression Ratio	18:1
Rated Power	3.6 kW (5 HP) @1500 RPM

Table 3 – Details of the selected test fuel.

FIP (bar)	Diesel share (%)	Biodiesel share (%)	Hydrogen share (lit/min)	Notation
500	100	0	0	D100IP500
1000	100	0	0	D100IP1000
1500	100	0	0	D100IP1500
500	0	100	0	B100IP500
1000	0	100	0	B100IP1000
1500	0	100	0	B100IP1500
500	0	100	5	B100H1IP500
1000	0	100	5	B100H1IP1000
1500	0	100	5	B100H1IP1500
500	0	100	7	B100H2IP500
1000	0	100	7	B100H2IP1000
1500	0	100	7	B100H2IP1500
500	0	100	9	B100H3IP500
1000	0	100	9	B100H3IP1000
1500	0	100	9	B100H3IP1500

operations, especially for 500 bar FIP. This is because the pilot fuel being injected just 5bTDC ignites late and produces combustion away from the TDC. As a result, lower cylinder temperature is generated which leads to lower cylinder pressure.

As the injection pressure increases, the finer atomization of the fuel reduces the ignition delay and aids in better combustion that can be observed in the form of improved combustion pressure profiles of the engine [55]. As the pilot fuel injection timings are advanced to 11° and then 17bTDC, the liquid fuel gets more time to vaporize, atomize and burn to release more of its heat energy closer to the TDC, which resulted in higher pressure developments near to TDC. This also produced higher efficiencies, as shown in Fig. 4. The increased injection pressure of 1000 bar and 1500 bar further increased the cylinder pressure for 11°as well as for 17bTDCpilot injection.

It is also observed in Fig. 2 (D-F) that the increase in hydrogen flow rates elevated the cylinder pressure for all FITs and FIPs, especially in 11bTDCand 17bTDC pilot injections. This is because of the advancement of FIT, which provides more time for mixing of vaporized pilot fuel with the hydrogen-air mixture to form more homogeneous fuel-air mixture. This allowed quicker ignition and subsequent better combustion of the air-fuel mixture closer to the TDC. It is also observed that, as the injection pressure is increased from 500 bar to 1000 bar and then to 1500 bar, the cylinder pressure for the B100H1 strategy increased gradually. This increase is more prominent with the advancement of FIT, as increasing FIPs increased the atomization of the liquid fuels and aided in better combustion. Further, an increase in hydrogen participation to 7lit/min (represented as B100H2 in Fig. 2(G-I)) and then to 9 lit/min (represented as B100H3in Fig. 2(J-L)) shows a consistent increase in cylinder pressure with advancement in FIT as well as with the increase in FIP. It is also noticed that when the FITs are advanced, the peak pressure of the hydrogen-biodiesel strategies comes closer to the TDC. This is because of the early ignition of charge due to the higher flame speed of hydrogen. It is also observed that the increase in FIP and advancement of FIT have allowed higher participation of hydrogen under dual fuel strategies. This is due to the advancement in FIT, which allows better mixing of the liquid fuel vapour, hydrogen and air. This ultimately allows more homogeneous combustion, whereas, increase in FIP reduces the viscous effect of the biodiesel and allows better atomization of the fuel droplets. This eventually improves the nature of combustion. Among all the tested conditions, the highest

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Table 4 – Total percentage of uncertainty of computed performance parameters.

Computed performance parameter	Measured Variables	Instrument involved in measurement	% Uncertainty of measuring instrument	Total % uncertainty of computed parameters
BP	Load	Load sensor	0.2	1.02
		Load indicator	0.1	
	RPM	Speed measuring unit	1.0	
BSFC	Fuel consumption	Fuel measuring device	0.065	1.02
		Fuel flow transmitter	0.05	
	BP	As given for measuring BP	1.02	
BSEC	BSFC	As given for measuring BSFC	1.02	1.44
	BP	As given for measuring BP	1.02	

Table 5 – Total sampling uncertainty and standard deviation of emission parameters.

Sampled emission	Average total sampling uncertainty (%)	Average standard deviation
CO	0.916	0.3
UHC	1.510	0.9
NO_X	1.208	0.7
Smoke opacity	0.461	0.00365

cylinder pressure of 72.06 bar is attained with the 9lit/min hydrogen flow rate (B100H3) at a FIT of 17bTDC and FIP of 1500 bar, which is 15.80% higher than base diesel operation and 21.02% higher than pure biodiesel operation at the same operating conditions.

Heat release rate

Heat release rate represents the combustion quality in terms of the heat released per crank angle rotation. The HRR is calculated from the cylinder pressure variation using the Eq. (2).

$$HRR = \frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1}\left(P\frac{dV}{d\theta}\right) + \frac{1}{\gamma - 1}\left(V\frac{dP}{d\theta}\right) + \frac{dQ_w}{d\theta} \quad (2)$$

The variation of the HRR of the engine at different FITs and FIPs is plotted in Fig. 3(A-L). It can be seen from Fig. 3(A-C) that the HRR for the pure biodiesel operation at retarded FIT (5bTDC) is lower than base diesel operation at all FIPs. Moreover, it is also observed that the peak heat release for the biodiesel operation appeared closer to TDC as compared to base diesel operation, indicating better premix combustion owing to the higher cetane number of the biodiesel [56]. As the FITs are advanced to 11bTDC and then 17bTDC, the deficit between HRRs of base diesel and pure biodiesel operation became smaller. At 17bTDC FIT, the biodiesel operations have shown almost similar HRRs as compared to base diesel operations. It is also noticed that the HRRs for all the single and dual fuel operations are increased with increasing FIPs. This is because of the better atomization of the liquid fuels that leads to the formation of a more homogeneous mixture and subsequent better combustion of the air-fuel mixture [57]. This improvement in HRR with increasing FIP is more important in case of biodiesel as the higher injection pressure improves the atomization of biodiesel, which has a higher viscosity than diesel. This allows better liberation of the heat energy of the biodiesel, thus providing higher power output.

The variation of HRR for the biodiesel-hydrogen dual fuel operations with increasing hydrogen flow rates at three different FITs and FIPs are shown in Fig. 3 (D-L). It is seen from the graphs that, with pilot fuel injection at 5bTDC, the HRRs of all three hydrogen strategies are lower than the base diesel. The pilot injection is too late during the compression stage to produce sufficient ignition energy required for the combustion of hydrogen-rich charge in the vicinity of the TDC. As a result, the peak HRR is observed away from the TDC. However, it is also observed that the increasing FIP marginally improves the HRR due to better atomization and subsequent better combustion of the pilot fuel. As the FIT is advanced to 11bTDC, the pilot fuel got a little bit more time to initiate ignition and ignite the hydrogen-enriched charge. As a result, the utilization of hydrogen is more prominent, which is further evident from the increased HRR of the engine. With further advancement of FIT to 17bTDC, the further increase in HRR for the hydrogen strategies can be observed. It is also worth mentioning that the higher hydrogen participation (shown as B100H2 and B100H3) shows much higher HRR at FIPs of 1000 bar and 1500 bar.

Performance characteristics

Brake thermal efficiency (B_{th})

Fig. 4 delineates the variations of B_{th} for varying FIPs and FITs of hydrogen-biodiesel dual fuel strategies. It is noticed from the figure that the B_{th} decreases for base biodiesel operations at all FIPs and FITs as compared to base diesel operation. This is primarily because of the lower calorific value of the biodiesel, due to which the total heat release from the combustion of biodiesel is less. Consequently, the work output is also less and a higher amount of fuel needs to be injected into the engine to sustain the load. Further, the higher viscosity of the biodiesel also hampers the injection and atomization of the fuel, due to which the combustion is also not proper, and this also hinders effective utilization of the fuel energy. It is also noticed that the increase in FIP to 1000 bar and then to 1500 bar improves the B_{th} of the engine as the higher injection pressure improves atomization and aids in the combustion process. The advancement of FIT to 11bTDC and then to 17bTDC is also beneficial in increasing B_{th} as injection advancement provides better mixing of liquid fuel spray in the hydrogen–air mixture. This allows majority of the fuel to burn in the premix phase and then the flame gradually burns the residual hydrogen through flame propagation. Thus, majority of the fuel burns in the early stage of power stroke and provides higher power output and higher efficiency [58]. The

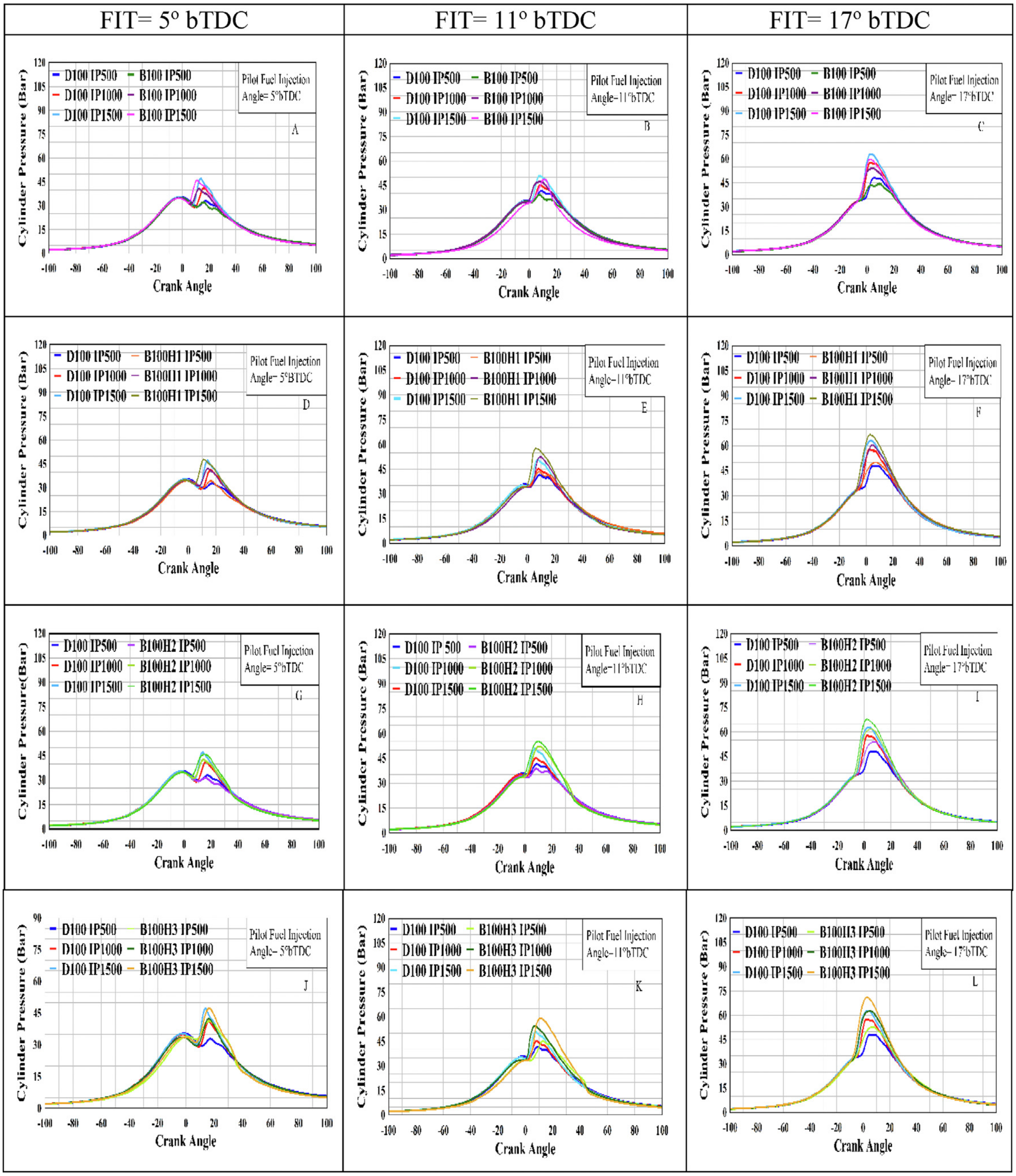

Fig. 2 — (A–L)-Variation of cylinder pressure for varying FIPs and FITs.

hydrogen dual fuel operation with pilot biodiesel improves the B_{th} of the engine in all FITs. This is because of the higher calorific value of hydrogen that increases the available heat energy in the combustion chamber [59].

Further, the advancement in FIT also improves the B_{th} by improving the quality of fuel-air mixture. Additionally, it also provides larger premixed phase of combustion that allows larger heat release closer to TDC due to the higher flame velocity of hydrogen. Moreover, the B_{th} of the engine also increased with increasing FIP of the pilot fuel. This is because higher injection pressure reduces the viscosity effects of biodiesel, which improves combustion and ultimately results in higher B_{th}. Amongst all hydrogen-biodiesel strategies, the B100H3 approach has the highest B_{th} of 32.15% at 17bTDCpilot FIT and 1500 bar FIP, which is 8.46% higher than the base diesel operation and 11.36% higher than pure biodiesel operation at the same conditions.

Brake specific energy consumption

Fig. 5 shows the deviation of BSEC with respect of varying FIPs and FITs of pilot biodiesel for different hydrogen dual fuel strategies. It is noticed from the figure that the BSEC is higher for Jatropha biodiesel as compared to base diesel operation at almost all FIPs and FITs. This is because of poor fuel atomization of the Jatropha biodiesel caused by the higher viscosity of Jatropha biodiesel and lower calorific value of the biodiesel [60].

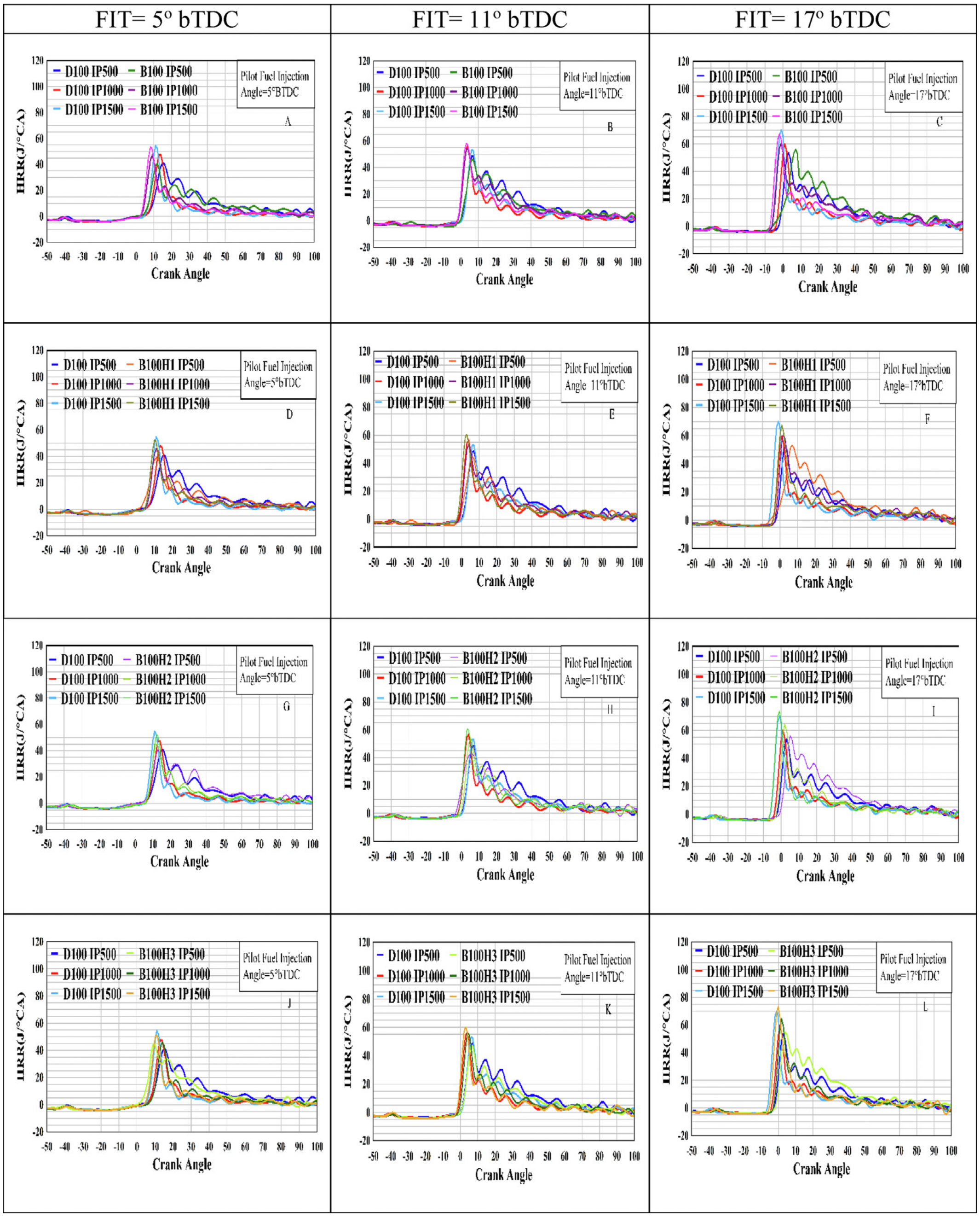

Fig. 3 – (A–L) - Variation of heat release rate for varying FIPs and FITs.

However, with the advancement in FITs, the BSEC decreases for all tested fuels. This is because of the advancement in FIT provides marginally higher time for the biodiesel droplets to mix with air and dissociate into smaller hydrocarbons, which can burn with relative ease [61]. It is also fascinating to notice that, by increasing the FIPs there is a notable decrease in BSEC for tested fuels, especially for biodiesel operations. The decrement in BSEC can be attributed to reducing the droplet size of the injected fuel at higher FIP. A more homogeneous fuel-air mixture is possible at higher FIP, which causes an improvement in combustion quality. It is noticeable that the hydrogen dual fuel operation with biodiesel as pilot fuel results in the reduction in BSEC of the dual fuel engine. This is primarily because of the much higher calorific value of the hydrogen that delivers major proportion of the energy during combustion and thus reduces the BSEC. Additionally, the higher flame velocity of hydrogen enhances the combustibility of hydrogen-biodiesel vapour-air mixture and allows a quicker and more complete combustion [62]. Thus, it allows better utilization of the heat energy and reduces the BSEC.

Emission analysis

Oxides of nitrogen emissions

Fig. 6 shows the variation of NO_X emissions for hydrogen-biodiesel strategies at different tested FITs and FIPs. It can

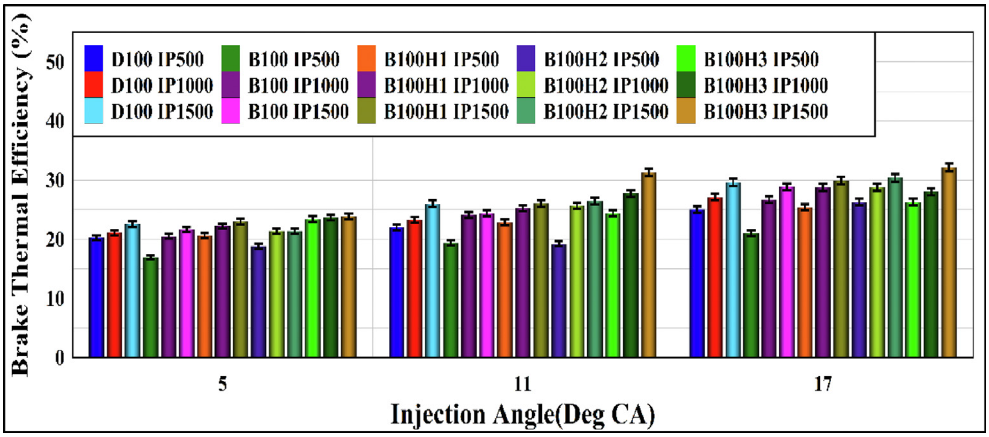

Fig. 4 — Variation in B_{th} with varying FIPs and FITs.

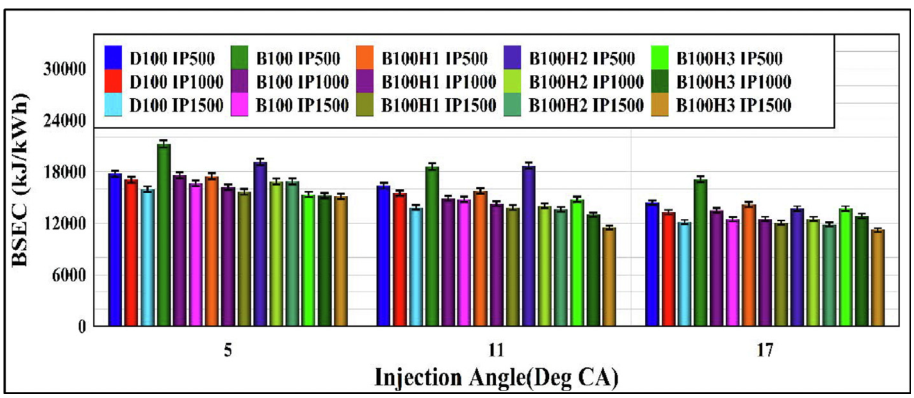

Fig. 5 — Variations in BSEC with varying FIPs and FITs.

be seen from the graph that the NO_X emissions from the engine is much lower for 5°bTDC injection for all tested fuels. This is because of the late injection of the liquid fuels, which reduces the combustibility of the charge and produces a lower in-cylinder temperature. As NO_X emissions are primarily formed at higher cylinder temperatures [63], hence the low temperature combustion may be initiated by delayed injection of fuel, which reduces the NO_X emissions at the expense of reduced work output indicated by reduced B_{th}(witnessed in Fig. 4). It is also observed that the NO_X emissions are gradually increased with the increasing FIT, as this allows more homogeneous mixing of the fuel-air mixture, leading to better combustion and higher cylinder temperature. Further, the increase in liquid FIP is also found to increase NO_X emissions as it improves the fuel atomization and mixing of fuel droplets with air. Similar increasing trends of NO_X emissions were also testified by *Yeandand Boehman* [62]. This feature are primarily observed with biodiesel operation as the higher FIP reduced

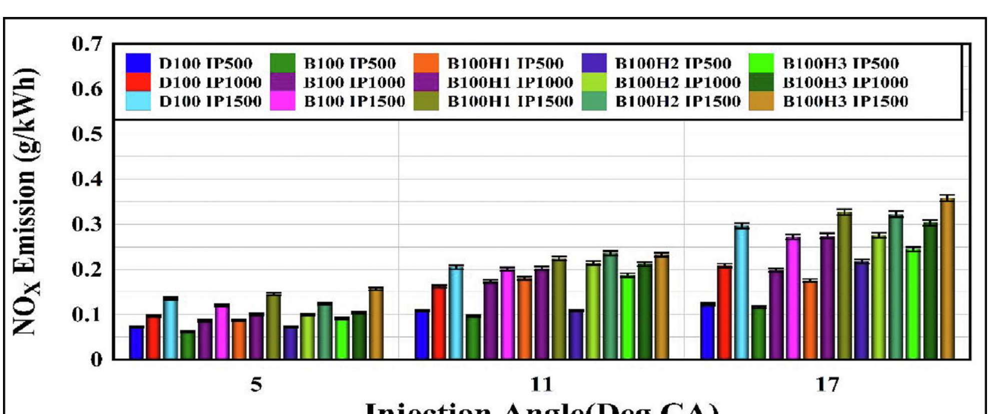

Fig. 6 — Variation of NO_X emissions with varying FITs and FIPs.

the viscous effect. It is also observed that the effect of increasing FIP is more prominent in case of advanced FITs for all engine operations. As the advancement of fuel injection along with higher injection pressure allows quick distribution of more homogeneous air-fuel mixture inside the entire volume of the cylinder [63]. This, in terms, improves the premixed phase of combustion and allows higher power output with penalties of higher NO_X emissions. On the other hand, when hydrogen is introduced into the engine, the NO_X emissions from the engine are found to increase at all FITs and all FIPs. This is because of the higher calorific value and high flame velocity of hydrogen that promotes premixed combustion and thus increases the NO_X emissions. Further, the advancement in FITs and increase in FIPs are also increased the NO_X emissions under hydrogen dual fuel strategies as both improved combustibility of the charge. *Jhanget al.* [64], *Deb* et al. [65], *Chiriac and Apostolescu* [66] have also reported the increasing trend of NO_X emission with the addition of hydrogen under dual fuel mode.

UHC emission

The presence of UHC in the tail pipe emission indicates the degree of incompleteness of the combustion process. More complete combustion produces less UHC as the maximum of the hydrocarbon dissociates to release its chemical energy as heat energy. Fig. 7 indicates the variation of UHC emission in respect of varying FIPs and FITs for the tested single fuel and hydrogen dual fuel operations. It is noticed from the figure that the Jatropha biodiesel shows a higher UHC emission than the diesel at almost all the experimental operating conditions. This is because of the higher viscosity of biodiesel that tends to retard the burning rate, because of which the incompleteness in combustion increases and generates higher UHC emission in contrast of diesel fuel. Advancement in FIT improves the burning charge and induces to a slight improvement in UHC emission of Jatropha biodiesel. This is because injection advancement provides more time for the fuel droplets to mix with hot air inside the combustion chamber and reach ignition temperature. It is also noticed that the increase in injection pressure is also improved the UHC emissions as higher injection pressure reduces the size of fuel droplets that allows the droplets to vaporize quickly and form a homogeneous air-fuel mixture [67,68].

The incorporation of hydrogen into Jatropha biodiesel clearly shows a massive reduction in UHC emission. This may be attributed to the reduction of the carbon content of the fuel by hydrogen addition, which causes lower UHC emission [69]. Moreover, the higher flame velocity of hydrogen improves the pilot fuel combustibility and consequently results in lower UHC emission. The advancement in FIT causes a significant reduction in UHC emission of the Hydrogen-Jatropha biodiesel strategies. The advanced FIT provides more time for the combustion of the pilot fuel and leads to lower UHC emission. *Kose and Ciniviz* [70], *Saravanan and Nagarajan* [71] have also obtained similar results.

CO emission

Fig. 8 shows the variations in CO emission in respect of varying FIPs and FITs. It is seen from the figure that the Jatropha biodiesel shows a higher CO emission than the diesel at almost all the experimental conditions. The higher viscosity of the Jatropha biodiesel causes a slower burning rate and promotes more CO emission than diesel [72]. However, with increasing FIPs, the CO emission is also found to decrease. Due to higher FIP, comparatively finer liquid fuel droplet size is obtained, that assists in better combustion and generates lower CO emissions [73]. The hydrogen dual fuel operation with biodiesel pilot operation is also found to distinctly reduce the CO emission for all dual fuel strategies. It happens because of the hydrogen induction, which reduces the cumulative carbon content of the fuel [74]. Further, the higher burn rate of hydrogen also allows the dissociation of hydrocarbons into carbon particles and then to carbon dioxide [75]. The advancement in FITs lowers down the CO emission by ensuring enough time for preparing the homogeneous mixture. The obtained outcomes are similar to the findings of *Karagoz* et al. [49], *Zhou* et al. [76], *Koseand Ciniviz* [70].

Soot emission

Fig. 9 encapsulates the variation of soot emission with respect to varying FIPs and FITs of Hydrogen-Jatropha biodiesel strategies. It is noticed from the figure that the Jatropha biodiesel produces higher soot emission than the diesel at all experimental conditions. This is because of the larger droplet size due to higher viscosity of Jatropha biodiesel than the neat diesel fuel [77]. At higher FIPs, the soot emission is observed to be lower, because higher injection pressure improves the atomization and helps in proper burning of the biodiesel [78]. The addition of hydrogen to Jatropha biodiesel brings down the carbon to hydrogen ratio inside the combustion chamber

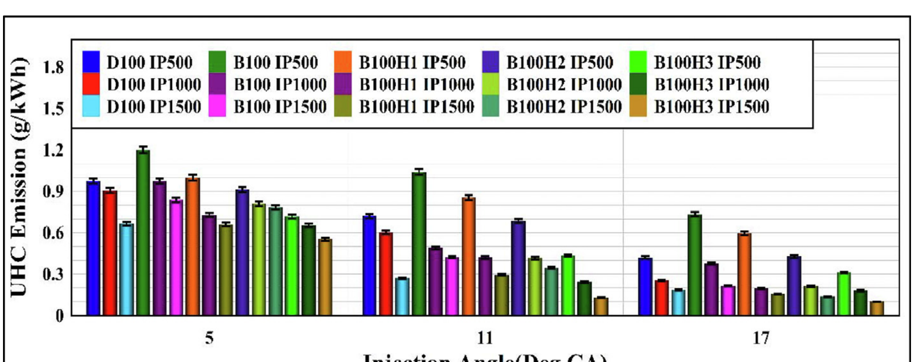

Fig. 7 — Variation of UHC emission with varying FITs and FIPs.

Please cite this article as: Kumar M et al., Effect of pilot fuel injection pressure and injection timing on combustion, performance and emission of hydrogen-biodiesel dual fuel engine, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.06.260

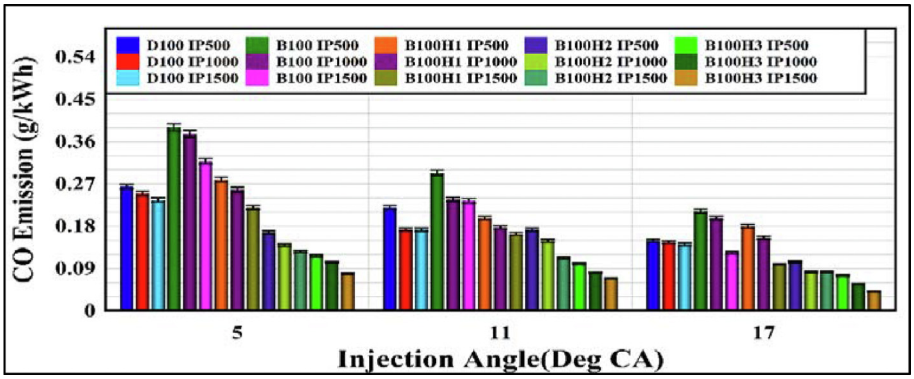

Fig. 8 – Variation of CO emission with varying FITs and FIPs.

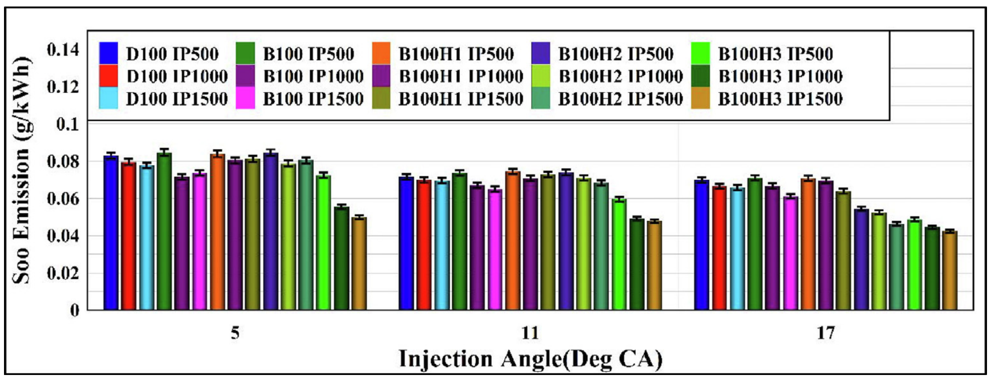

Fig. 9 – Variation of soot emission with varying FITs and FIPs.

and therefore reduces the formation of soot particles [79]. It is also found that the soot emission is reduced with the increase of hydrogen flow rate [75,80]. It is also noticed that, with the advancement of FITs, the soot emission is remarkably reduced. The advanced FIT offers more homogeneous combustion, which enhances the combustion rate and leads to lower soot emission [81].

Conclusion

The experimental investigation is conducted on a partially modified single-cylinder, four-stroke, water-cooled CI engine at a maximum output of 3.6 kW and a constant speed of 1500 RPM under dual fuel mode. The engine is operated with diesel in single fuel mode and with hydrogen-biodiesel combinations in dual fuel mode with three different hydrogen flow rates of 5lit/min, 7lit/min and 9lit/min, respectively. By varying the FIPs and FITs of pilot biodiesel, the dual fuel combustion process is partially controlled. The vital findings of the present experimental work under dual fuel strategies are summarized below:

- The advancements in pilot fuel injection timings improved the combustion pressure and brought the peak pressure closer to TDC. Major improvement in combustion pressure is observed with higher injection pressure and higher hydrogen participation. The highest cylinder pressure of 72.09 bar with 17°bTDC injection timing, 1500 bar injection pressure and 9lit/min hydrogen flow rate.
- The HRR for the base biodiesel operation decreased under all operating conditions. However, the HRR of base biodiesel operation improved with higher injection pressure and advancement in injection timing the maximum HRR of 66.07 J/°CAis attained at 1500 bar injection pressure and 17°bTDC injection angle for base biodiesel operation. Addition of hydrogen gradually improved the HRR with both injection timing advancements and injection pressure increase. Highest HRR of 73.74 J/°CA for hydrogen dual fuel operation is attained with 7lit/min hydrogen flow rate with pilot injection advancement of 11°bTDC and injection pressure of 1500 bar. This indicated that higher pilot injection pressure and advancement in injection angle is beneficial for higher utilization of HES under dual fuel operation.
- The performance of the engine is much lower under retarded pilot injection angle of 5°bTDC for all fuel combinations. However, with increase in injection pressure marginally improved the $B_{th}$and BSEC of the engine, especially under hydrogen-biodiesel dual fuel operations with higher hydrogen participation. The highest B_{th} under this condition is found to be 23.81% with 9lit/min hydrogen flow rate and 1500 bar pilot injection pressure. As the injection angle is advanced to 11°bTDC, then to 17°bTDC, the improvement is much prominent with maximum B_{th} of 31.23% and 32.15% respectively, obtained with 9lit/min hydrogen flow rate, and 1500 bar pilot injection pressure.

- The NO_X emissions from the engine are much lower at 5°bTDC pilot injection because of the shorter premix phase of combustion. Increase in injection pressure improved the combustibility of the charge and increased the NO_X emissions. Hydrogen participation also increases the NO_X emissions, which are more prominent at higher flow rates and injection pressure. As the injection angle is advanced, the NO_X emissions from the engine also increased. However, NO_X emissions are observed to be consistently high for hydrogen operations. The maximum NO_X emissions of 0.358 g/kWh are observed with 9lit/min hydrogen flow rate, and 1500 bar pilot injection pressure.
- The UHC, CO and soot emissions from the engine improved with injection advancement and injection pressure increase. However, increasing hydrogen participation is found to be more effective in the reduction of the above-mentioned emissions. The hydrogen-biodiesel operation with 9lit/min hydrogen flow rate, and 1500 bar pilot injection pressure produced 59.52% decrease in UHC, 77.62% decrease in CO emission and 46.15%decrease in soot emissions at 11°bTDC pilot injection angle. and,

It is observed from the present experimental study that the pilot injection angle and injection timing can be effectively used to guide the combustion process. Further, it is also observed that the injection angle advancement can be an effective way to improve the combustion process and hence, further injection advancements can be attempted to assess the quality of combustion process. Lastly, the effectiveness of the injection angle advancement and elevated injection pressure can be studied under dual fuel operations with other gaseous and liquid fuels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge the kind support of the DST, Government of India under the scheme HFC 2K18 (Sanction No: DST/TMD/HFC/2K18/96).

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