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Comparison of the hydrogen powered homogeneous charge compression ignition mode with multiple injection schedules and the dual fuel mode using a twin-cylinder engine

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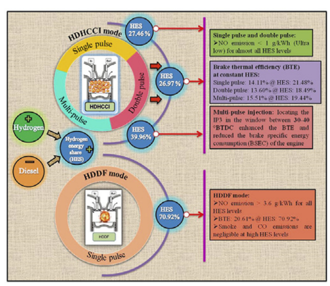
HIGHLIGHTS

- Injection schedule influence the hydrogen diesel HCCI (HDHCCI) mode.
- Single pulse HDHCCI mode provides ultra-low NO emission for entire HES levels.
- No significant change in performance of HDHCCI with double pulse injection.
- Multi-pulse HDHCCI mode recovers the combustion and increases the HES level.
- Multi-pulse enhances the performance of HDHCCI mode and reach near to HDDF mode.

GRAPHICAL ABSTRACT



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ABSTRACT

The present work discusses the influence of injection schedules in hydrogen diesel homogeneous charge compression ignition (HDHCCI) mode, the experiments were carried out in three distinct diesel injection schedules like single pulse, double pulse and multi-pulse at low load operation. The maximum reachable hydrogen energy shares (HES) are 27.46%, 26.97% and 39.96% for a single pulse, double pulse and multi-pulse respectively. For almost all HES levels, the single pulse and double pulse HDHCCI mode provided ultra-low NO emission when compared with hydrogen diesel dual fuel (HDDF) mode. The multi-pulse injection increased the brake thermal efficiency (BTE) compared with single pulse and double pulse injection, since the timing of injection pulse 3 (IP3) in multi-pulse significantly altered the combustion characteristics of HDHCCI mode. Locating the IP3 in the window of

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Injection schedules
Comparison study
Hydrogen diesel dual fuel mode

30–40 °BTDC (before cool flame) enhanced the BTE and reduced the brake specific energy consumption (BSEC) of the engine.

Introduction

In the near future, hydrogen is anticipated to be an important energy carrier, since it is abundant, free from carbon atoms and can be generated from renewable sources. The reaction between one oxygen atom and two hydrogen atoms lead to high energy release and formation of water, this is performed either in the type of chemical reaction in the fuel cell or in the kind of combustion in an internal combustion engine (ICE). In the case of fuel cell, it has a potential to meet the future demand, however for a midterm solution the ICE is better than fuel cell, since lower cost related to the availability of existing engine components unlike the use of rare earth materials in the fuel cell and it does not demand high purity of hydrogen like fuel cell [1,2].

In the homogeneous charge compression ignition (HCCI) mode, the lean homogeneous charge is compressed to the point of auto-ignition to attain the combustion, where auto-ignite at multiple locations without apparent flame propagation. The HCCI combustion mode significantly faster than spark ignition (SI) or compression ignition (CI) modes, this combustion entirely controlled by chemical kinetics, unlike SI and CI combustion controlled by the spark plug and fuel injector. In this combustion mode, the compression effect of the flame front and burned gas are absent, thus it leads to high temperature in the localized regions are removed therefore it resulted in low oxides of nitrogen (NO_x) emissions. The fuel-rich zones are not formed due to lean homogeneous mixture within the cylinder; therefore soot formation is also avoided. However, the level of hydrocarbon (HC) and carbon monoxide (CO) emissions are notably higher than conventional combustion mode [3,4].

The HCCI kind of combustion was first introduced by Onishi et al. [5] in a two stroke engine, authors reported that fuel conversion efficiency and engine stability were enhanced while exhaust emission, vibration and noise were decreased. Subsequently, Najt and Foster [6] conducted the experiments in HCCI mode using isooctane and n-heptane as fuel in a four-stroke engine, they revealed that HCCI combustion fully controlled by chemical kinetics. In the case of liquid fuels, preparing homogeneous charge and avoiding fuel wall impingement are paramount important in HCCI mode [7]. The control of auto-ignition of the charge to properly phase the combustion is the crucial task in HCCI mode, if high combustion rate made to happen at a correct crank angle in the engine cycle, the high thermal efficiency can be obtained [8]. The difficulties present in achieving proper combustion phasing tackled by the intake charge temperature, variable compression ratio, variable valve timing and addition of high cetane fuels like diethyl ether, diesel, dimethyl ether, etc [9,10].

Hydrogen is considered as a suitable fuel for HCCI mode because of its few important properties as follows: (1) Southwest research institute researchers suggested the Elevated Pressure Auto Ignition Temperature (EPAIT) for typical HCCI fuel is 823 K, this temperature level is close to hydrogen auto-ignition temperature (858 K), (2) High diffusivity (2.65–3.25 m/s) and flame speed (0.63 cm^2/s) lead to easy formation of the homogenous mixture and better combustion, (3) Wider flammable limit (4–75%vol) makes the engine to operate extreme level of low equivalence ratio, (4) Small amount of hydrogen (mass basis) could deliver a high power due to high energy content (120 MJ/kg), (5) Better anti-knock properties because of its high octane rating (130) (6) Less ignition source to initiate the combustion and carbon free energy [4,11]. There is coupled effects make hydrogen as a suitable fuel for HCCI combustion than conventional combustion mode (SI or CI), that is (a) During combustion with oxygen it produces only water as a byproduct, but with atmospheric air it also provides some NO_x due to thermal detachment and oxidation of nitrogen (N_2) in air. (b) Hydrogen allows constant combustion while extremely diluted situations due to low level of lean flammability. In HCCI mode, the extreme lean condition creates quite low combustion temperatures, which avoids the formation NO_x and near-zero engine emission can be achieved if hydrogen as a fuel [12–14].

Stenlaas O et al. [15] investigated the neat hydrogen fuelled HCCI mode and reported that hydrogen HCCI mode was possible for very lean equivalence ratios ($\lambda > 3$ to $\lambda = 6$). The inlet air temperature was considered as a most influencing parameter to control the ignition timing of hydrogen fuelled HCCI mode and the range of intake air temperature was narrow as the mixture getting richer. The level of NO_x emission was insignificant at maximum thermal efficiency condition. The CO and HC emissions were detected in the engine exhaust and lubricating oil was only the source for this emission. Moreover, high level of unburned hydrogen in the range of 3000–7000 ppm was presented in the exhaust. A similar study conducted by Caton and Pruitt [16], their experimental results suggested that hydrogen fuelled HCCI mode was suitable and viable for the compression ratios nearly 17 to 20 at both 80 °C and 100 °C of intake air temperature. The highest indicated thermal efficiency was 21% at an IMEP of 2.1 bar, which was lower than the conventional diesel mode. Ibrahim and Ramesh [17] carried out the hydrogen fuelled HCCI mode to study the effect of intake charge temperature, authors reported that this mode was feasible with the equivalence ratio and intake charge temperature ranging from 0.19 to 0.3 and 130-80 °C at a constant compression ratio of 16:1. The maximum brake mean effective pressure (BMEP) was 2.2 bar, at this highest BMEP, the maximum thermal efficiency reached to 24.2%. The level of NO_x emission was negligible as compared with conventional diesel combustion. The minimum charge temperature for any equivalence ratio provided the high thermal efficiency because of proper combustion phasing. The pressure rise rate and peak pressure within the cylinder were higher for neat hydrogen HCCI mode when matching against CI mode. Increase in inlet air temperature resulted in a decrease in thermal efficiency and IMEP, since the mass flow rate of air was decreased with increase in intake charge temperature [18].

Taking neat hydrogen fuelled HCCI mode into an account, intake air temperature needs to be varied to sustain the combustion because hydrogen required high auto-ignition temperature to initiate the combustion process. Ibrahim and Ramesh [19] also focused on hydrogen diesel HCCI (HDHCCI) mode, this mode is not demanding intake air temperature sweep to sustain the combustion, instead of that, diesel used as an ignition initiator. However, this mode can be achieved from a neat diesel HCCI mode by increasing the hydrogen energy ratio. The brake thermal efficiency (BTE) was improved as hydrogen addition increases by delaying the combustion phasing since it was too advanced combustion in neat diesel HCCI mode. The highest energy ratio and lowest energy ratio was limited due to the risk of misfire and knock. Authors found that retarded injection timing provided the best thermal efficiency as energy ratio progresses. The level of NO emission was declined with hydrogen energy ratio for all operating levels because of reduction in combustion rate with energy ratio. However, single pulse diesel injection led to impingement of diesel on the wall thus it affected the CO, HC and smoke emissions significantly. Guo et al. [20] analyzed effect the hydrogen enrichment in diesel HCCI engine, authors used manifold diesel injection to attain diesel HCCI combustion mode, their research work suggested that hydrogen addition decreased the combustion duration and retarded the combustion process. Thereby, thermal efficiency and engine power output were improved. The level of CO emission per unit burned diesel mass and indicated specific NO_x emission were decreased with hydrogen addition, however HC emission per unit burned diesel was not significantly influenced by hydrogen enrichment. Typical combustion properties of diesel compared with hydrogen are listed in Table 1 [11,21].

Injection characteristics perform a major role in emission and combustion characteristics of HCCI mode, especially multi-pulse injection (Injecting the fuel in multiple shots instead of single shot at proper timing) improves the combustion and reduces the engine out emission in a considerable level [22–24]. In diesel HCCI mode, injecting diesel in early injection timing to form homogeneous mixture led to wall impingement due to low temperature and pressure prevailed in the cylinder, thus it increased the level of smoke and HC emission in the exhaust [9,25,26]. Zheng and Kumar [27] adopted the multi-pulse diesel injection in HCCI combustion mode using a common rail CI engine. Their results suggested that at low load operation parallel reduction of smoke and NO_x emission was achieved by preparing a lean homogeneous mixture with the use of multi-pulse injection strategy. In multi-pulse, injecting one diesel pulse near the top dead centre (TDC) improved the combustion phenomena and reduced the wall wetting of HCCI engine, authors also found that reduced diesel quantity and advanced last injection timing decreased the overall NO_x emission in the exhaust. Nathan et al. [28] reported that high smoke and HC emissions observed in single pulse injection at early injection timing due wall impingement, adoption of multi-pulse significantly increased the BTE and reduced the level of smoke and HC emissions as compared with single pulse in HCCI mode. Moreover, keeping one of the injection pulses close to the cool flame zone improved the phasing of the combustion process, thereby overall output was also enhanced. Mathivanan et al. [29] showed that multi-pulse injection in diesel HCCI mode increased the thermal efficiency from 11% (single pulse) to 15% at low load condition, in multi-pulse injection, the concentration of smoke and HC emissions were lower by 56% and 24% than single injection due to reduction in wall wetting. The level of NO_x emission for multi-pulse was higher than a single pulse, however which not high as conventional combustion. The retarded timing and reduced duration of last injection pulse in multi-pulse provided the low NO_x emission. Authors also reported that there was no significant influence of earlier injection pulses in combustion phasing when the last injection happened at near TDC. Abdul Rahman and Ramesh [30] investigated the split injection strategy in biogas-diesel fuelled partially premixed charge compression ignition (PPCCI) engine at a BMEP of 2 bar. It may be noted that the authors divided the total fuel quantity into two injection pulses for split injection. Because of better combustion phasing, the split injection enhanced the efficiency of the engine than single pulse, the smoke level was reduced as a result of improvement in homogeneity and reduction in wall wetting for entire biogas energy share range. The reduced second diesel pulse lowered the high combustion rate by the cause of reduced heterogeneity in the mixture.

Motivation and aim of the present research work

As a whole from the literature, limited research work has been performed in hydrogen fuelled HCCI engine with diesel as an ignition initiator in the form of HDHCCI mode, the wall wetting is the major issue in single pulse HDHCCI mode as a result of early injection. It is expected that multi-pulse injection could solve the above issue with an improvement in performance. In addition, none of the research output is found on multi-pulse diesel injection strategy in hydrogen fuelled HCCI engine. Hence, it is worthwhile to study the effect of multi-pulse injection in combustion, performance and emission characteristics of HDHCCI mode compared with single pulse and double pulse injections strategy in the same mode in a CI

Table 1 – Combustion properties of hydrogen and diesel.

Properties (Units)	Hydrogen	Diesel
Energy density at 100 kPa and 15 °C (MJ/m^3)	10.3	35.8
Lower heating values (MJ/kg)	120	43
Auto ignition temperature (K)	858	530
Density at 100 kPa and 15 °C (kg/m^3)	0.0083	848
Flame velocity (m/s)	2.65–3.25	0.3
Stoichiometric air fuel ratio	34.2	14.5
Flammability limits in air (%)	4–75	0.7–5
Minimum ignition energy (mJ)	0.02	–
Diffusivity in air (cm^2/s)	0.63	0.038

engine with twin-cylinder. Moreover, the same engine was operated in the hydrogen diesel dual fuel (HDDF) mode under similar operating condition. Eventually, the comparison made between the HDHCCI and HDDF combustion modes.

Experimental apparatus

A naturally aspirated, twin-cylinder, four-stroke, CI engine was used to run in the HCCI mode, this mode was performed both the cylinders simultaneously. An eddy principle-based dynamometer was coupled with the engine to apply load and to keep the speed of the engine constantly. Photographic view and schematic representation of the experimental setup for HDHCCI mode are illustrated in Fig. 1 and Fig. 2. A separate line was used to perform the hydrogen induction in the engine, which consists of flame arrestor, water trap, needle valve, hydrogen mass flow meter, regulator and hydrogen cylinder. Here, for safety purpose, water trap and flame arrester were kept to prevent the backfire moving to hydrogen source from the engine, the hydrogen flow rate was measured with the help of thermal mass flow meter on a mass basis, precise control of flow rate of hydrogen was done with use of needle valve in the hydrogen line. The flow rate of diesel was directly measured on the mass basis, a displacement type flow meter was used to calculate the flow rate of air on the volume basis, which was mounted on the surge tank. A catalytic principle-based hydrogen gas detector was used to perform the leak test before starting any kind of experiments in the HDHCCI mode.

In the cylinder head, a piezoelectric pressure sensor was flush mounted to measure the in-cylinder pressure, the emissions of NO, CO and HC were monitored by using portable exhaust gas analyzer, a filter paper-based smoke meter was used to perform the smoke measurement, a KiBox cockpit was used to acquire the crank angle and in-cylinder pressure data for 100 consecutive cycles, then which processed to compute the heat release rate (HRR). The test engine specifications are listed in Table 2 and the equipment used for the experiments is listed in Table 3. The coolant temperature was controlled using thermostat valve, which was monitored continuously by using a K-type thermocouple, the exhaust gas temperature was measured using another thermocouple. The injection timing, duration, rail pressure and diesel injection pulses were altered using fully accessible open electronic control unit (ECU) in an automotive twin-cylinder engine. The uncertainty for the measured and calculated parameters were computed and are listed in Table 4, sensitivity of major equipment used for experiments is given in Table 5.

Execution procedure

Initially, the engine was operated in CI mode, once the coolant temperature reached 80 °C, the combustion mode shift was carried out from CI to HCCI by injecting diesel at advanced injection timing. For all the experiments, the engine load, speed and intake charge temperature kept at 2 bar, 1800 rpm and 37 °C constantly. In diesel HCCI mode, higher injection pressure may results into finer atomization and high degree of homogeneity, this is vice versa for lower injection pressure [31–33], but splitting the number of pulses at high injection pressure is difficult due to low injection duration. Hence, injection pressure was kept at mid range nearly 50 MPa to prepare a good mixture and also facilitate for the split injection, this injection pressure constantly maintained for all the experiments. Later, the HDHCCI mode was commenced by admitting hydrogen into the air intake manifold of the engine, however the hydrogen leak test has been carried out before initiating the experiments related to HDHCCI mode using hydrogen gas detector. Precisely controlled hydrogen was sent through flame arrestor and water trap to the engine for safety reason. The methodology for conducting the experiments on HDHCCI and HDDF modes is illustrated using the flowchart in Fig. 3. In order to increase the hydrogen energy share (HES) as mentioned in Equ. (1), diesel energy needs to be decreased initially, thus it reduced the BMEP of 2 bar and then hydrogen energy should increase to maintain the fixed BMEP. Similarly, the BMEP kept constant for subsequent energy shares.

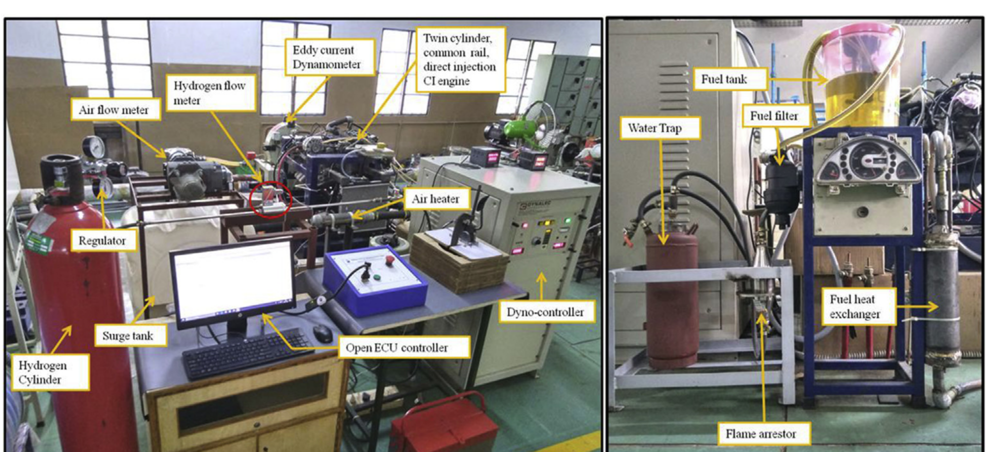

Fig. 1 – Photographic view of the experimental setup for HDHCCI mode.

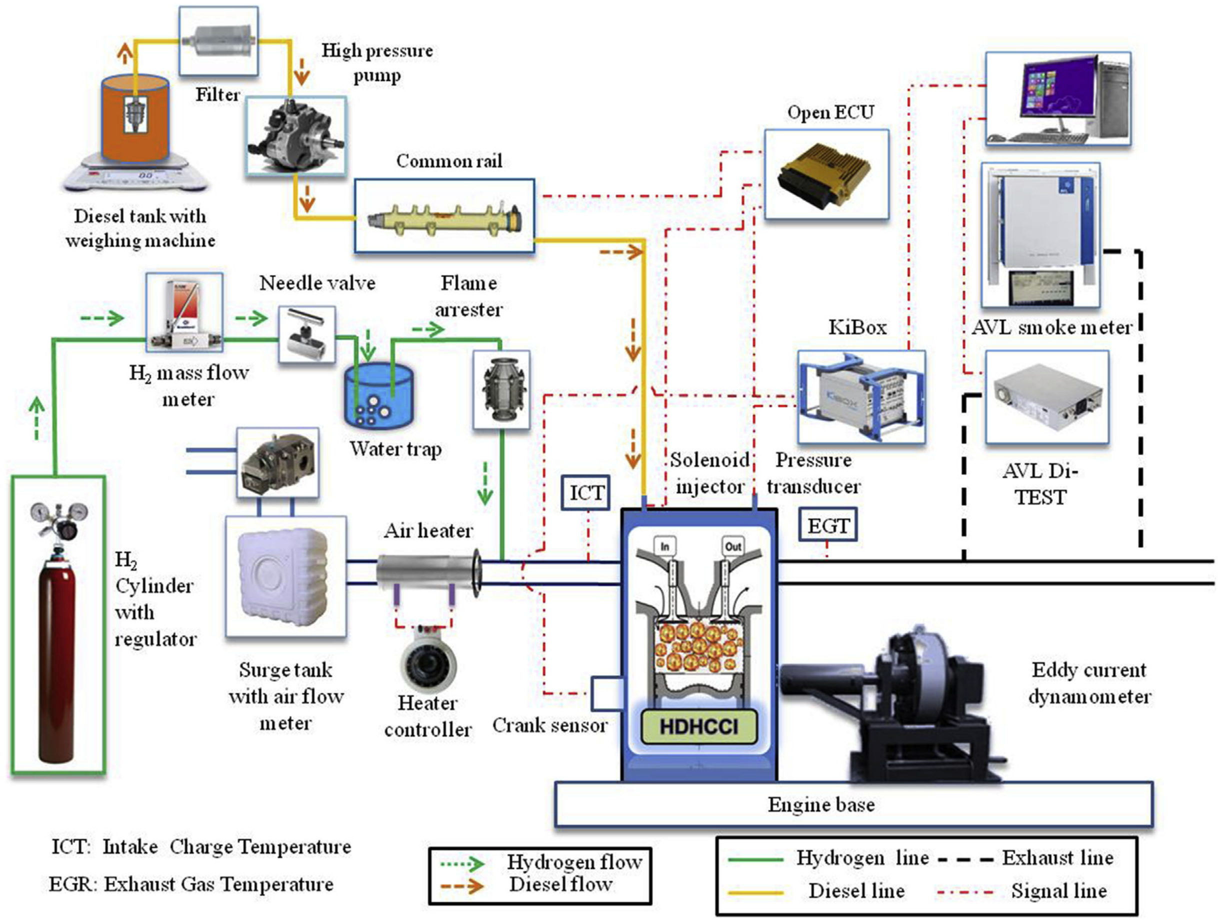

Fig. 2 – Schematic representation of the experimental setup for HDHCCI mode.

$$HES\ (\%) = \frac{\dot{m}_{hydrogen} \times CV_{hydrogen}}{\dot{m}_{hydrogen} \times CV_{hydrogen} + \dot{m}_{diesel} \times CV_{diesel}} \times 100 \qquad (1)$$

Where.

$\dot{m}_{hydrogen}$: Flow rate of hydrogen in kg/s

$\dot{m}_{diesel}$: Flow rate of diesel in kg/s.

$CV_{hydrogen}$: Lower calorific value of hydrogen in kJ/kg.

CV_{diesel}: Lower calorific value of diesel in kJ/kg.

Injection schedule

The single pulse HDHCCI mode was conducted by injecting diesel at a single injection pulse (IP) in early injection timing with increasing HES, the optimum injection timing was found at each HES in terms of thermal efficiency point of view. Subsequently, early injection of diesel was split evenly into two or double injection (IP1: 50% and IP2: 50%) to improve the homogeneity of the mixture, which is named as double pulse HDHCCI mode. In order to improve the combustion phasing and ignition quality, the third pulse (10%) was introduced near TDC to act as an ignition improver, which is labeled as multi-pulse HDHCCI mode (IP1: 45%, IP2: 45% and IP3: 10%). Eventually, the HDDF mode was also conducted in the same

Table 2 – Test engine specifications.

Compression ratio	18.5:1
Displacement volume	909 cc
Bore & stroke	83 & 84 mm
No. of cylinders	2
Injection method	Common rail direct injection
Injector nozzle	7 hole
Cooling type	Water cooled
Connecting rod length	140.5 mm
Maximum power	18.64 kW @ 3600 rpm
Maximum torque	55 N-m @ 1800–2200 rpm

Table 3 – Details of the equipment used in the experiments.

Equipment name	Make and model
Piezoelectric pressure sensor	Kistler, 6052C
KiBox cockpit	Kistler, Type 2893A
Displacement type air flow meter	Flow Meter Group, FMR DN80 G100
Hydrogen mass flow meter	Bronkhorst, F-113AC-M50-AGD-55-V
Gas detector for hydrogen	Riken Keiki, GP-03
Open ECU	Nira, i7RS
Thermocouples	K-type
Exhaust gas analyzer	AVL Di-Test, GAS 1000
Smoke meter	AVL, 415S

Table 4 – Uncertainty for the measured and calculated parameters.

Parameters	Uncertainty
Dynamometer torque	±0.63%
Dynamometer speed	±0.08%
Coolant temperature	±1.25%
HC	±5.86%
CO	±5.53%
NO	±3.35%
Smoke	±9.66%
Cylinder peak pressure	±1.14%
Hydrogen energy share (HES)	±0.51%
Brake thermal efficiency (BTE)	±0.56%

Table 5 – Sensitivity of major equipment used for experiments.

Major Equipment	Sensitivity
Piezoelectric pressure transducer	20 pC/bar
KiBox cockpit	0.03 pC/s
Thermal mass flow meter for hydrogen	<0.05% FS/°C (0.0001 kg/h °C)
Exhaust gas analyzer	0.05 ± 0.01 μA/ppm
Smoke meter	20 μg/m^3-10 mg/m^3

operating condition to compare with HDHCCI mode, this combustion mode was achieved by injecting single diesel pulse at conventional injection timing. However, for any injection schedule, the injection timing of each pulse was decided based on the thermal efficiency, which will be discussed in section Injection timing. The graphical illustration of diesel injection schedules for both HDHCCI and HDDF modes at HES of 0% are depicted in Fig. 4. It may be noted that the crankcase dilution effect was noticed while conducting the experiments on HDHCCI mode at HES of 0% (neat diesel HCCI operation) due to low pressure and temperature prevailed in the cylinder at very advanced injection timing, thus some amount of diesel passed through the piston ring and diluted the engine oil [34]. Therefore, the brake specific energy consumption (BSEC) is higher in HDHCCI mode as compared with HDDF mode to maintain the same BMEP of the engine, this will be seen later in section Influence of injection schedules in performance characteristics of HDHCCI mode. The BSEC is calculated using Equ. (2) and (3).

$$BSEC\ (MJ/kWh) = \frac{\dot{m}_{hydrogen} \times CV_{hydrogen} + \dot{m}_{diesel} \times CV_{diesel}}{Brake\ power} \quad (2)$$

$$Brake\ power\ (kW) = \frac{2\pi \times N \times T}{60000} \quad (3)$$

Where.

$\dot{m}_{hydrogen}$: Flow rate of hydrogen in kg/hr
$\dot{m}_{diesel}$: Flow rate of diesel in kg/hr.
$CV_{hydrogen}$: Lower calorific value of hydrogen in MJ/kg.
CV_{diesel}: Lower calorific value of diesel in MJ/kg.
N: Engine speed in rpm.
T: Torque in N-m.

Results and discussion

The effects of injection schedules in characteristics of HDHCCI mode are described in detail along with a comparison of HDDF mode in the following sections.

Injection timing

Fig. 5 illustrates the optimum injection timing of diesel for each injection schedule under various energy shares. In diesel HCCI mode, retarded injection timing led to advanced combustion and high combustion rate, advanced injection timing led to delayed onset of combustion and reduced combustion rate (although not shown). When hydrogen is added in diesel HCCI mode, retarded the combustion and lowered the combustion rate, which will be shown later, hence it has been noticed that retarded diesel injection timing provided the improved thermal efficiency as HES increases. Similar outputs also found in the literature [19], therefore single pulse had to retard with a rise in HES as seen from Fig. 5. In a similar manner, double pulse (IP1 and IP2) injection schedule also provided the best efficiency at retarded injection timing with HES. In multi-pulse injection schedule, the best injection timing for IP1, IP2 and IP3 have been retarded up to the HES of 19.44% for the best thermal efficiency, beyond this HES level the engine was misfired. In order to increase the HES from the above level, IP1 and IP2 kept constant and IP3 was advanced with HES to sustain the combustion, which is named as multi-pulse HDHCCI (extension) mode. The influence of IP3 in multi-pulse on characteristics of HDHCCI mode will be discussed later in section Influence of IP3 (multi-pulse) in characteristics of HDHCCI mode.

Influence of injection schedules in combustion characteristics of HDHCCI mode

The variation of in-cylinder pressure and HRR for HDHCCI and HDDF modes with HES are depicted in Fig. 6, the HES of 0% exhibit the peculiar two stage HRR for all injection schedules in HDHCCI mode as seen from the figure. The first stage of HRR indicates the cool flame and the second stage of HRR indicates the main combustion process. The single pulse HDHCCI mode at 0% HES led to advanced combustion phasing and high combustion rate. As initial hydrogen admission takes place, the combustion rate is increased, further increase in hydrogen fraction, the combustion rate is decreased and retarded towards TDC, thus it improved the performance of the engine. It may be noted that chemical and dilution effect of hydrogen delayed the combustion process and reduced the combustion rate [20]. Reduction in level of OH^- radicals during cool flame stage due to interaction with hydrogen, which is the chemical effect ($H_2 + OH = H_2O + H$), the dilution effect is because of reduction in oxygen concentration and diesel within the cylinder with hydrogen addition. The maximum possible HES

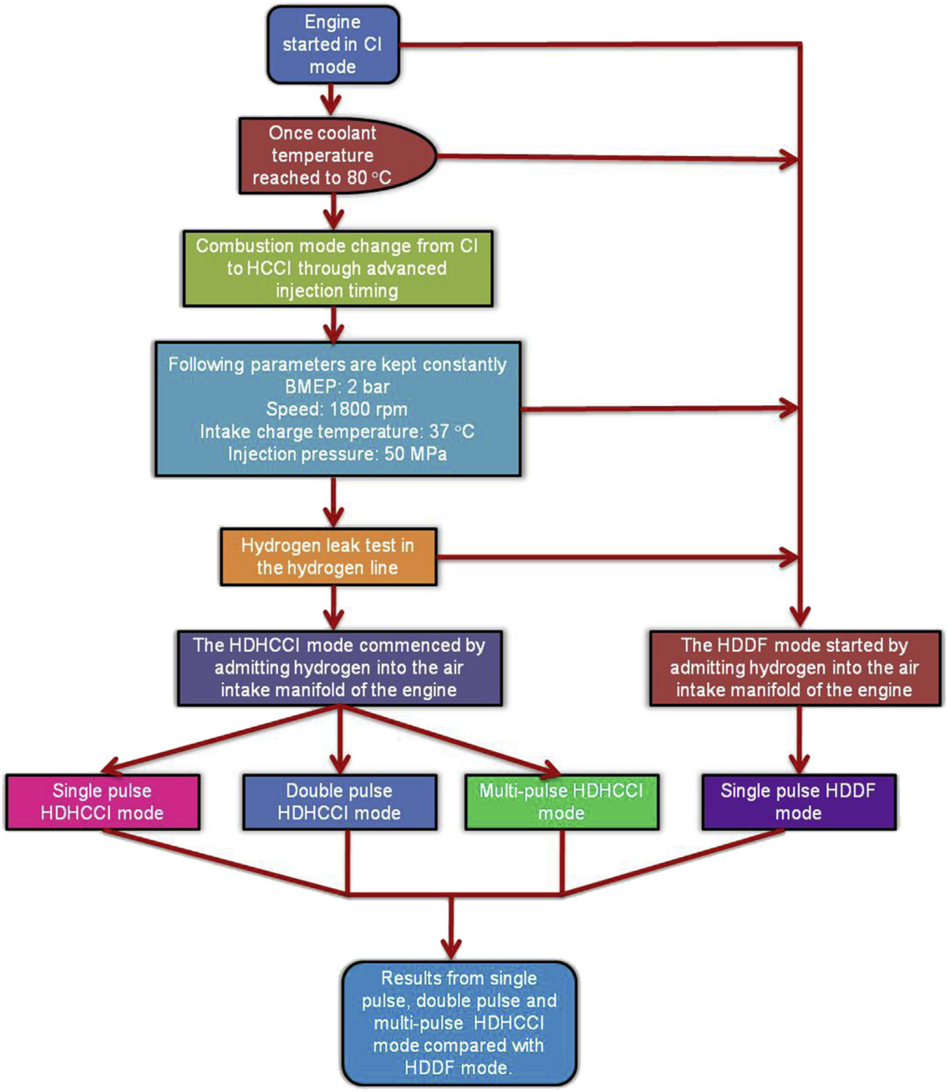

Fig. 3 – Experimental methodology for HDHCCI and HDDF modes.

reached to 27.46%, due to single diesel injection hard to ignite the occupied hydrogen-air mixture in the cylinder, therefore it led to misfire. Hence, as seen from Table 6, the coefficient of variance (COV) of IMEP increased from 6.40% to 7.73% and rate of pressure rise (RoPR) is decreased to from 5.01 to 3.18 bar/°CA at maximum HES condition.

In double pulse HDHCCI mode, total diesel quantity split evenly into two pulse (IP1: 50% and IP2: 50%) to improve the homogeneity of the mixture and the best injection timings of both the pulses are retarded with HES as explained earlier. The cool flame is clearly visible for neat diesel HCCI case like single pulse HDHCCI mode at HES of 0%. Most importantly, spitting the diesel fuel atomize and vaporize the liquid fuel more easily than single injection thus it intensified the high temperature (main) combustion stage with hydrogen addition up to the HES of 18.49%. In addition, hydrogen chemical and dilution effect led to a delay in HRR with a rise in HES as seen from Fig. 6. As HES reached above 27%, the engine went to misfire zone due to more retarded combustion and low combustion rate before it reached to maximum BTE level. Therefore, the COV of IMEP increased from 5.31% to 8.50% and RoPR decreased from 5.07 bar/°CA to 3.96 bar/°CA at highest HES level.

On the other hand, in multi-pulse injection, total diesel quantity split into three IPs (IP1:45%, IP2:45% and IP3:10%). Alike last two injection schedules, retarded combustion and reduced combustion rate were noticed with hydrogen addition, beyond 19.44% of HES level, there was an erratic operation and the engine was misfired because of too retarded combustion in multi-pulse HDHCCI mode. The COV of IMEP raised from 8.03% to 9.9% and RoPR reduced from 4.59 bar/°CA to 3.79 bar/°CA. The operating range of HES is increased from 26.69% to 39,96% by advancing the IP3 timing. When last injection (IP3) is advanced, the entire combustion is recovered and advanced as seen from Fig. 6 (multi-pulse HDHCCI mode), this also increased the BTE which will be discussed in section Influence of injection schedules in performance characteristics of HDHCCI mode. It is observed from the figure that HES of 26.69% and 39.96% have two peak HRR, the first peak related the IP3 and second peak related to earlier IP1

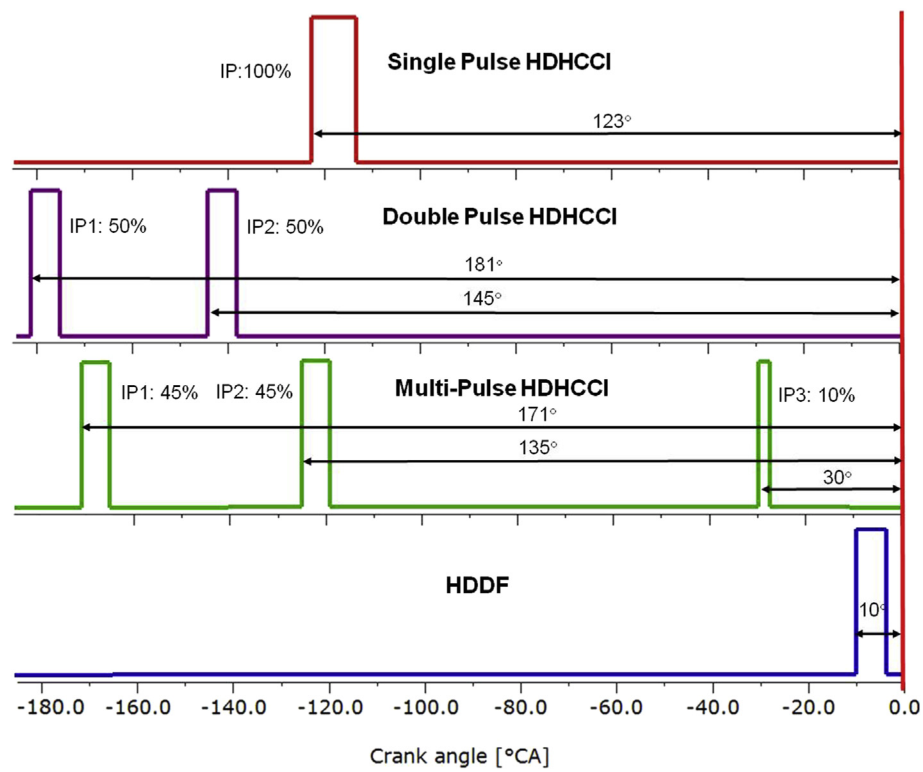

Fig. 4 – Graphical illustration of injection schedules at HES of 0% for HDHCCI and HDDF modes.

and IP2. In this multi-pulse extension case, the COV of IMEP and RoPR reached to 10.10% and 4.18 bar/°CA at maximum HES level. The highest level of HES for this injection schedule is 39.96%, this was due to hardware limitation restrict the maximum diesel reduction for the respective speed and load condition in multi-pulse HDHCCI mode.

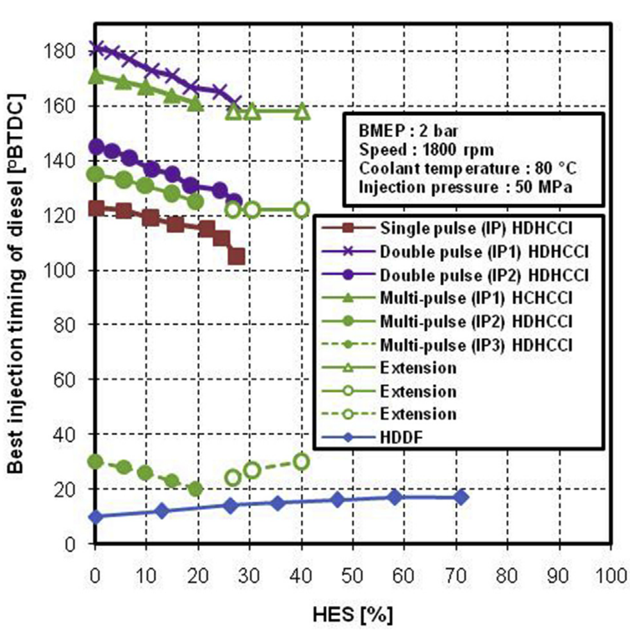

Fig. 5 – Variation of best injection timing of diesel with HES.

In the case of HDDF mode, single peak HRR is observed like conventional combustion. It is seen from Fig. 6 that with a rise in HES, the combustion rate is decreased, phasing is advanced and combustion duration is increased. As HES reaching maximum level, HRR decreased significantly, the maximum level of HES restricted to 70.92%. This was because of weak ignition source of diesel (in dual fuel mode) difficult to ignite the high level of hydrogen-air charge in the cylinder, thus the engine went to misfire region. High cycle to cycle variation has been noticed at high energy share, therefore the COV of IMEP reached to 14.36%, it may be noted that the COV of IMEP for the regular operation of the vehicle does not exceed 10% [35]. The RoPR is also increased up to the HES level of 60% and then dropped down at maximum HES condition.

Influence of injection schedules in performance characteristics of HDHCCI mode

The change in BTE and BSEC for HDHCCI and HDDF modes are depicted in Fig. 7(a). For single pulse HDHCCI mode, too advanced combustion in neat diesel HCCI mode led to low BTE nearly 9.40% @ HES:0%, as energy share progresses the BTE enhanced to 15.21% @ HES: 27.46%. Since hydrogen's chemical and dilution effect delayed the combustion phasing towards TDC and BSEC also decreased with HES, thus it improved the overall work output of the engine. This similar increasing trend is followed for double pulse and multi-pulse HDHCCI mode with increase in energy share.

However, for a constant energy share (nearly 20%), the BTE and BSEC for the single pulse, double pulse and multi-pulse HDHCCI modes are 14.11% & 25.50 MJ/kWh, 13.60% & 26.45

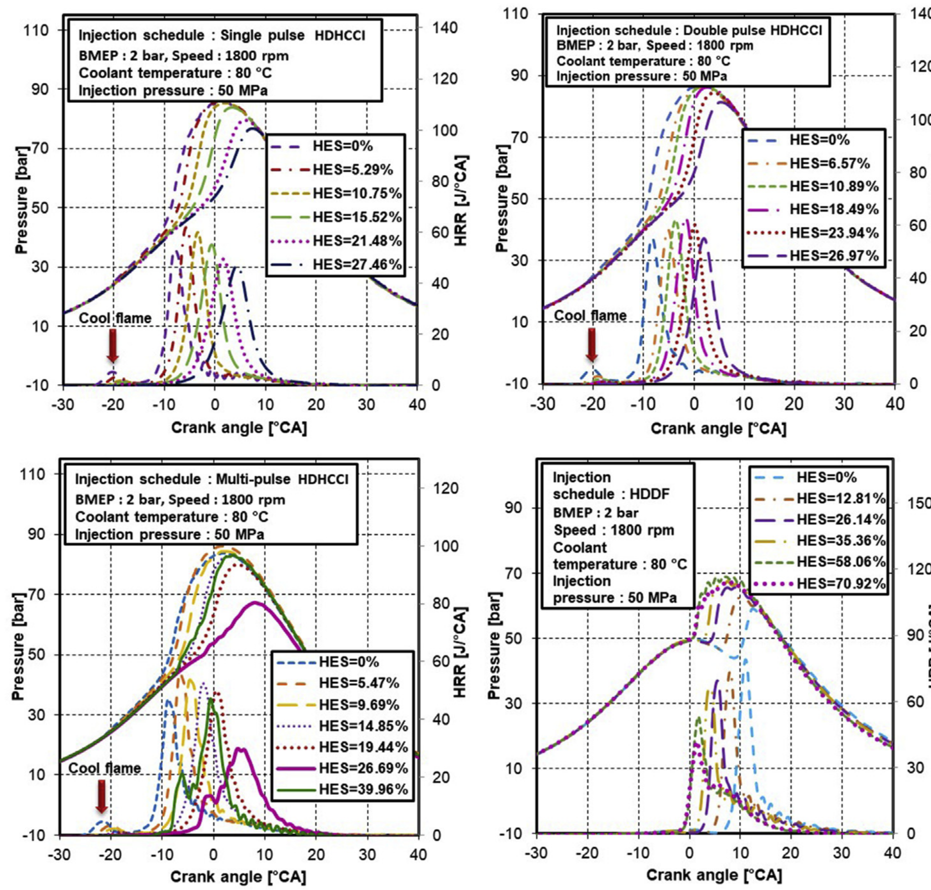

Fig. 6 – Influence of HES on combustion characteristics of HDHCCI and HDDF modes.

Table 6 – Effect of HES in COV of IMEP and RoPR for HDHCCI and HDDF modes.

Single pulse HDHCCI			Double pulse HDHCCI			Multi-pulse + Extension HDHCCI			HDDF		
HES (%)	COV of IMEP (%)	RoPR (bar/°CA)	HES (%)	COV of IMEP (%)	RoPR (bar/°CA)	HES (%)	COV of IMEP (%)	RoPR (bar/°CA)	HES (%)	COV of IMEP (%)	RoPR (bar/°CA)
0	6.40	5.01	0	5.31	5.07	0	8.03	4.59	0	5.31	1.54
5.29	5.98	5.15	3.18	5.47	5.12	5.47	7.07	4.97	12.81	6.33	1.69
10.75	6.45	4.97	6.57	5.46	5.04	9.69	8.65	4.72	26.14	6.94	2.07
15.52	6.11	4.50	10.89	5.41	5.06	14.85	8.47	4.39	35.36	7.88	2.32
21.48	7.03	3.66	14.70	5.78	4.96	19.44	9.90	3.79	46.91	9.34	2.47
24.56	6.90	3.78	18.49	6.36	4.93	26.69	14.67	1.95	58.06	12.50	2.60
27.46	7.73	3.18	23.94	6.39	4.53	30.46	10.27	4.48	70.92	14.36	2.28
–	–	–	26.97	8.50	3.96	39.96	10.10	4.18	–	–	–

MJ/kWh and 15.51% & 23.20 MJ/kWh, it is clear that multi-pulse increased the BTE due to lower BSEC and proper combustion phasing than other two injection schedules as seen from Fig. 7 (b). For all HES levels, multi-pulse enhanced the BTE than a single pulse and double pulse HDHCCI mode due to the small near TDC injection (IP3) improved the HDHCCI combustion, therefore the required fuel quantity to maintain BMEP was also reduced, hence BSEC decreased compared with a single and double pulse injection. Extended multi-pulse case further improved the BTE by advancing the combustion phasing as it was too retarded combustion process when HES approaching above 20%. In the case of HDDF mode, the BTE is decreased from 23.92% @ HES: 0% to 20.61@ HES: 70% due to a reduction in combustion rate and increased BSEC with HES. Hence, it is evident from Table 7 that at maximum HES condition the BTE and BSEC of multi-pulse extension HDHCCI version reached close to HDDF mode.

Influence of injection schedules in emission characteristics of HDHCCI mode

Fig. 8 depicts the influence of injection schedules in NO (brake specific basis) and smoke emissions for various HES levels. For single pulse HDHCCI mode, the ultra-low NO emission is

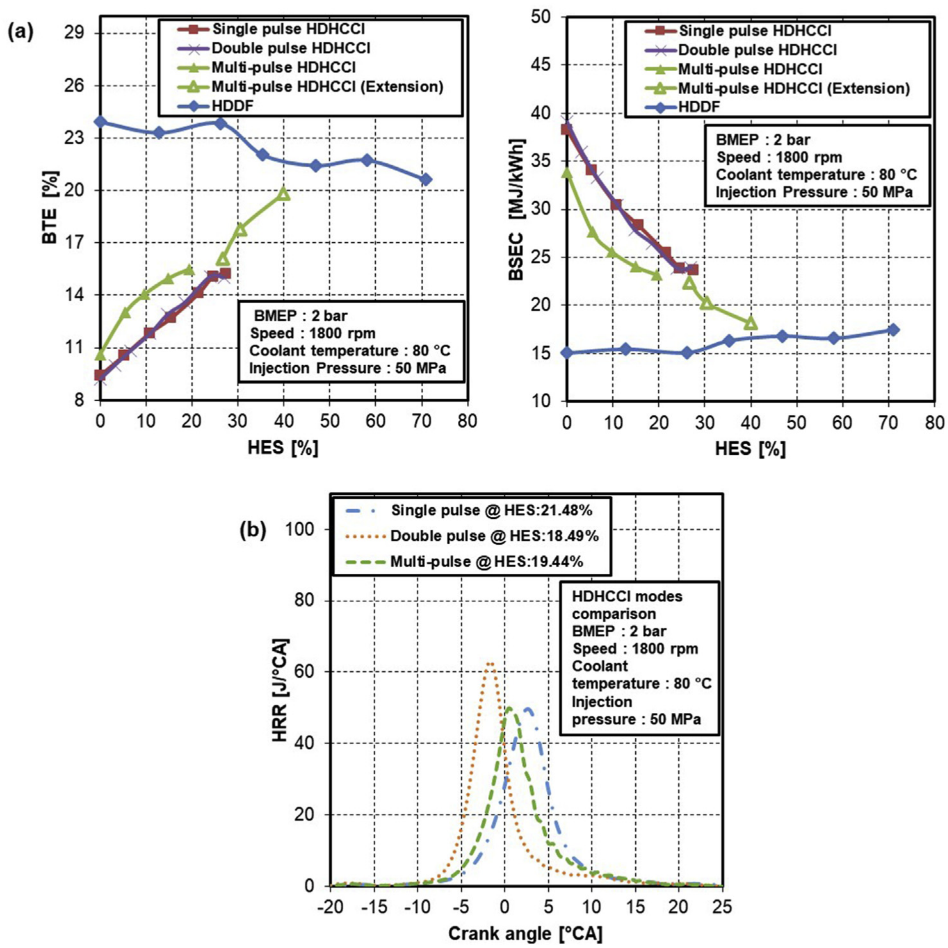

Fig. 7 – (a) Variation of BTE, BSEC for HDHCCI and HDDF modes (b) Effect of injection schedules on HRR for constant HES in HDHCCI mode.

obtained for the entire range of HES as a result of low temperature combustion. The level of NO emission is high at low energy shares in double pulse HDHCCI mode due to intensified main combustion at low HES levels as explained earlier in section Influence of injection schedules in combustion characteristics of HDHCCI mode, thus it increased the NO formation. At high HES levels, low HRR and more retarded combustion reduced the NO level as same as single pulse. In multi-pulse HDHCCI mode, the NO level is decreased linearly with HES due to retarded and reduced HRR with a rise in HES. In the case of multi-pulse extension, NO level is increased steeply due to rise in diffusion combustion by the cause of advanced injection timing of IP3 at high HES. For almost all HES levels for single and double pulse HDHCCI mode, the level of NO emission is lower than HDDF mode due to low temperature combustion by forming a lean homogeneous mixture within the cylinder. In multi-pulse case, the IP3 was injected near TDC to improve the combustion characteristics of HDHCCI mode, therefore it behaved like conventional combustion process and this resulted in higher NO emission than single and double pulse HDHCCI mode for entire HES level. In multi-pulse extension case, IP3 is more dominant than IP1 and IP2 which reflected as twin peak HRR as seen from Fig. 6, hence the level of NO went higher than any other mode of operation. It may be noted that with increasing HES, IP1 and IP2 diesel quantity only be reduced and IP3 kept constant with HES for multi-pulse & multi-pulse extension case of HDHCCI mode.

Table 7 – Comparison of performance between HDHCCI and HDDF modes at maximum HES condition.

Modes	HES (%)	BTE (%)	BSEC (MJ/kWh)
Single pulse HDHCCI	27.46 (Max)	15.21	23.66
Double pulse HDHCCI	26.97 (Max)	15.02	23.96
Multi-pulse HDHCCI	19.44 (Max)	15.51	23.20
Multi-pulse HDHCCI (Extension)	39.94 (Max)	19.83	18.14
HDDF	70.92 (Max)	20.61	17.45

For both HDHCCI and HDDF modes, the source of smoke emission is purely contributed by injected diesel since hydrogen is free from carbon atoms, therefore there is a decreasing trend in smoke emission with HES for any injection schedule as seen from Fig. 8. Adaptation of double pulse in HDHCCI mode has not shown a significant change in smoke emission for most of the energy shares when matching against single pulse. As injection schedule swift to multi-

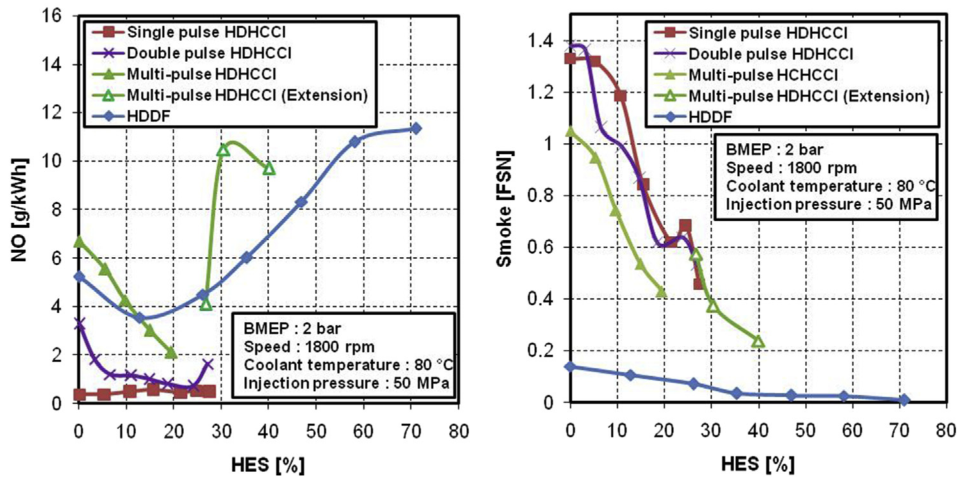

Fig. 8 – Variation of NO and Smoke for HDHCCI and HDDF modes.

pulse, the level of smoke is reduced for entire HES level, this was due to the near TDC injection rise the in-cylinder temperature thereby soot oxidation was improved. At low energy shares of HDHCCI mode for any injection schedule, diesel injection timing had to advance to lower the high combustion rate, this advanced timing possibly led to cylinder wall impingement because of low pressure and temperature prevailed in the cylinder, this brought high smoke emission than HDDF mode, moreover the amount of diesel used for HDHCCI mode was higher than HDDF mode for the same BMEP thus it also lowered the BTE and increased the BSEC as seen from Fig. 7(a). However, as energy share approaching high level in HDHCCI mode, smoke emission reduced close to HDDF mode due to the replacement of diesel fuel.

The variation of HC and CO (brake specific basis) emissions with HES for HDHCCI and HDDF modes are shown in Fig. 9. For single pulse HDHCCI mode at HES of 0%, high HC emission is observed when compared with any other modes, this was because lean homogenous mixture within the cylinder led to low temperature combustion. Moreover, earlier injection timing of diesel impinged on the cylinder wall that possibly led to wall wetting, this eventually ended in high HC emission. The concentration of HC emission is decreased as injection schedule shift to double pulse at energy share of 0%, due to reduction in wall wetting by splitting the total diesel quantity. As injection schedule moves to multi-pulse at HES of 0%, HC emission reduced further because of improvement in BTE and diesel fuel oxidation by near TDC injection. For any injection schedule in HDHCCI mode, level of HC emission need to be reduced with hydrogen addition, but this has not been seen from Fig. 9, because hydrogen enrichment reduced the diesel fuel oxidation heavily in the low temperature stage thus it led to rise or no change in HC emission with HES. However, it is evident from Fig. 9 that the level of HC emission in multi-pulse for entire HES sweep is lower than single and double pulse injection schedules in HDHCCI mode. In HDDF mode, overall HC emission is significantly lower for the entire HES range than any other HDHCCI modes due to low BSEC and high BTE.

For single pulse HDHCCI mode at HES of 0%, high CO emission is obtained as a result of poor post oxidation due to a low temperature that was prevailed in the cylinder, also early injection timing of diesel led to wall impingement. This CO

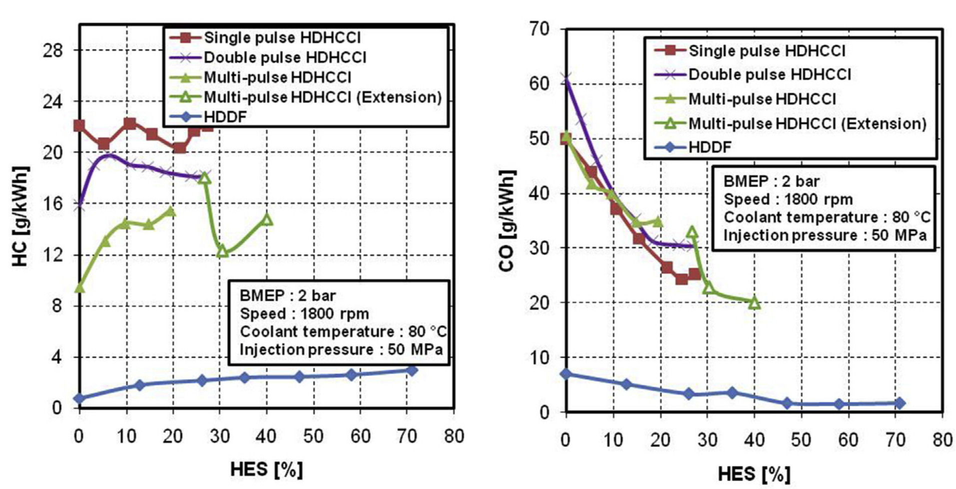

Fig. 9 – Variation of HC and CO for HDHCCI and HDDF modes.

Table 8 – Comparison of HDHCCI and HDDF modes with previous study.

Parameters	Single pulse hydrogen diesel HCCI mode @ HES: 41% (Max) (Ibrahim and Ramesh [19])	Single pulse HDHCCI mode @ HES: 27.46% (Max)	Double pulse HDHCCI mode @ HES: 26.97% (Max)	Multi-pulse HDHCCI mode @ HES: 39.96% (Max)	HDDF mode @ HES: 70.92% (Max)
Smoke (FSN)	0.856	0.456	0.532	0.238	0.01
NO (g/kWh)	0.195	0.504	1.66	9.69	11.34
HC (g/kWh)	0.309	22.01	18.16	14.82	2.99
CO (g/kWh)	16.40	25.22	30.32	20.10	1.65
Engine speed (rpm)	1500	1800	1800	1800	1800
Number of cylinders	Single cylinder	Twin-cylinder	Twin-cylinder	Twin-cylinder	Twin-cylinder
Compression ratio	16:1	18.5: 1	18.5: 1	18.5: 1	18.5: 1
Injector type	Single axial hole	Multi-hole	Multi-hole	Multi-hole	Multi-hole
BMEP (bar)	2	2	2	2	2

emission is further increased for double pulse at HES of 0%, this was due to more advanced injection timing of IP1 (nearly at bottom dead centre) led to over lean mixture thus it increased the CO emission level. As energy share increased, CO emission is decreased for both in HDHCCI and HDDF modes, this clearly reflected that diesel fuel replaced by hydrogen with a rise in HES. In any HDHCCI mode at very high energy shares, CO emission is not decreased for the respective injections schedule due to engine approached near misfire zone. Extended multi-pulse decreased the CO emission further because of an increase in HES. However, due to hardware limitation the HES level could not be extended for this mode, hence CO emission in multi-pulse HDHCCI mode is not decreased as the level of HDDF mode. Table 8 compared the

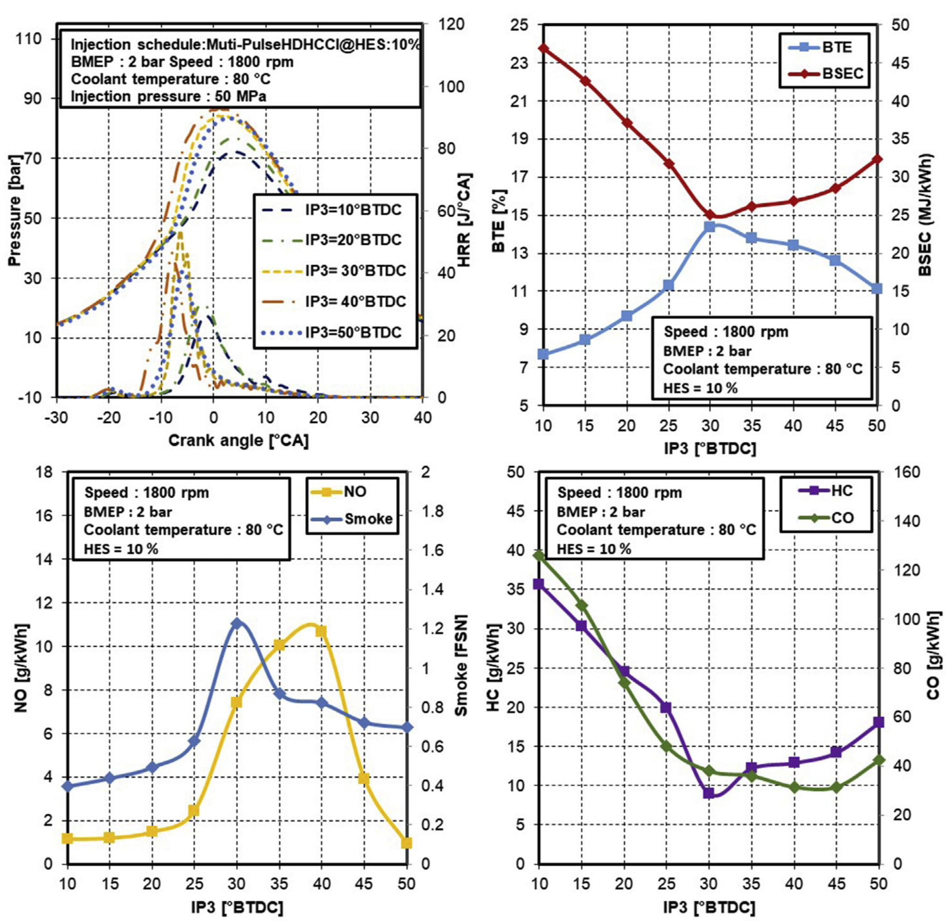

Fig. 10 – Influence of IP3 in characteristics of HDHCCI mode at constant HES.

present results of HDHCCI and HDDF modes with earlier study, it evident from the table that smoke emission is reduced significantly in multi-pulse HDHCCI mode compared with literature [19] due to reduction in wall wetting. However, use of single axial hole injector in the above literature, the HC emission was decreased considerable level.

Influence of IP3 (multi-pulse) in characteristics of HDHCCI mode

Fig. 10 illustrates the influence of last pulse (multi-pulse) in characteristics of HDHCCI mode, it is seen from the figure that as advancing the IP3 timing, the combustion process is advanced and combustion rate is also increased. However, as IP3 increased beyond 40 °BTDC, the combustion process is smoothed and phasing is retarded towards TDC. In addition, as advancing the last pulse timing, the time availability to create a homogeneous mixture was improved, hence the cool flame region is also improved. It is evident from Fig. 10 that the BTE is enhanced with a rise in IP3 up to 30 °BTDC due to increase in combustion rate and reduction in BSEC, further advancing the injection timing leads to decline in BTE because of reduction in combustion rate and increase in BSEC.

In the case of 10 °BTDC, the last pulse was not participated in main combustion process due to less time availability for mixture formation, therefore it was combusted nearly 10 °after TDC as seen from the HRR (small peak), thus it improved the soot oxidation level therefore level of smoke is low, whereas NO emission is not increased as a result of soot oxidation due to slight EGR like effect provided by the combustion product of last two injections [27]. The level of NO and smoke emissions both are not increased significantly up to 25 °BTDC, beyond this timing, smoke emission is increased significantly at 30 °BTDC due to neither soot oxidation nor homogeneity is presented in combustion hence smoke emission is worsened. When advancing the timing further, homogeneity factor in the mixture is enhanced, that it led to decline in smoke emission. On the other hand, the concentration of NO emission is increased at 40 °BTDC due to high rate of combustion and more advanced combustion phasing, as IP3 increased beyond 40 °BTDC, NO emission is reduced due to improvement in low temperature phenomena smoothed the overall combustion process. The level of HC and CO emissions are elevated when last injection pulse occurred at 10 °BTDC because of reduced combustion rate and high level of energy consumption, this emissions went down as IP3 advanced due to reduction in BSEC, advanced combustion and high combustion rate.

Conclusions

Based on the outcomes obtained from the experimental analysis on HDHCCI mode with different injection schedules and HDDF mode the following inferences are drawn:

- The maximum HES level restricted to 27.46% and 26.97% for single pulse and double pulse HDHCCI mode due to misfire. The multi-pulse HDHCCI (extension) mode increased the HES nearly 40% by advancing the injection timing of IP3 in multi-pulse injection schedule, the maximum HES reached to 70.92% in the case of HDDF mode.
- In HDHCCI mode with any injection schedule, the BTE was increased with a rise in hydrogen addition by retarding the combustion process towards TDC, since the combustion process was too advanced in neat diesel HCCI mode. Over the injection schedules at constant HES level in HDHCCI mode, multi-pulse enhanced the BTE compared with the single pulse and double pulse HDHCCI mode due to lower BSEC and proper combustion phasing. At maximum energy share, the efficiency of multi-pulse HDHCCI (extension) mode reached close to HDDF mode.
- The ultra-low NO emission was obtained at single pulse and double pulse HDHCCI mode as compared with HDDF mode for almost all energy shares. The level of NO emission was low only at high HES conditions in multi-pulse injection. However, for multi-pulse HDHCCI (extension) mode, the level of NO emission went high due to rise in diffusion combustion by the influence of IP3.
- The advanced diesel injection timing in single pulse HDHCCI mode resulted in wall impingement, thus it led to high smoke and HC emission. As injection schedule approached to multi-pulse HDHCCI mode, the level of smoke and HC emissions both were reduced for entire energy share due to improvement in performance and reduction in wall wetting.
- The IP3 was played major role in multi-pulse HDHCCI mode, injecting IP3 in the window of 30–40 °BTDC (before cool flame) improved the BTE and reduced the BSEC significantly. When IP3 kept at 50 °BTDC (far away from cool flame), the emissions were reduced heavily with a moderate level of engine performance.

On the whole, keeping the IP3 at safe crank angle window in multi-pulse HDHCCI mode improved the performance and reduced the engine out emissions in considerable level as compared with single and double pulse HDHCCI mode. The multi-pulse HDHCCI mode at high energy share able to stand beside with HDDF mode in terms of performance without affecting emissions, this is possible only by the proper capitalization of IP3 in the multi-pulse injection.

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.

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