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Effect of hydrogen–diesel dual-fuel usage on performance, emissions and diesel combustion in diesel engines

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Abstract
Diesel engines are inevitable parts of our daily life and will be in the future. Expensive after-treatment technologies to fulfil normative legislations about the harmful tail-pipe emissions and fuel price increase in recent years created expectations from researchers for alternative fuel applications on diesel engines. This study investigates hydrogen as additive fuel in diesel engines. Hydrogen was introduced into intake manifold using gas injectors as additive fuel in gaseous form and also diesel fuel was injected into cylinder by diesel injector and used as igniter. Energy content of introduced hydrogen was set to 0%, 25% and 50% of total fuel energy, where the 0% references neat diesel operation without hydrogen injection. Test conditions were set to full load at 750, 900, 1100, 1400, 1750 and finally 2100 r/min engine speed. Variation in engine performance, emissions and combustion characteristics with hydrogen addition was investigated. Hydrogen introduction into the engine by 25% and 50% of total charge energy reveals significant decrease in smoke emissions while dramatic increase in nitrogen oxides. With increasing hydrogen content, a slight rise is observed in total unburned hydrocarbons although CO_2 and CO gaseous emissions reduced considerably. Maximum in-cylinder gas pressure and rate of heat release peak values raised with hydrogen fraction.

Keywords
Hydrogen, diesel engine, smoke, NO_x, rate of heat release

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Introduction

Depletion of fossil fuels due to increase in energy demand causes fuel prices to rise; additionally, stringent emission regulations as a result of environmental concern create pressure on researchers in alternative fuel science. Depending upon European Union Commission's White Paper Report, transportation-related greenhouse gas emission is intended to be reduced by 60% in 2050 compared to 1990.[1] Renewable energy consumption in transportation industry raised from 3.5% to 3.8% between 2010 and 2011; it must reach 4.1% in order to cope with the intended target value.[1] In spite of reduced regulated emission levels thanks to the developments in

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technology, particulate matter (PM) fraction in tailpipe emissions increased.[2–4] According to air quality report in Europe,[1] PM ($\leq 10\,\mu$m) emissions increased by (beyond the predetermined levels legislated by World Health Organization) 43% in concentrated traffic zones, 38% in urban regions, 25% in industrial regions and even 15% in rural regions. Main reason of this situation is increase in diesel engine equipped vehicles.[1]

In parallel with these developments, environmentally friendly alternative fuel research in automotive industry such as liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG), biogas and ethanol has started. Hydrogen is a fuel without carbon element in its molecular structure and considered as an important fuel alternative which produces only water after combustion reaction. The usage of hydrogen in transportation industry designates it as the fuel of the future and gains attraction. Fuel cell technology with on-going development effort not yet satisfies requirement and the expectation in the market. The usage of hydrogen in internal combustion engines would provide a transition from hydrocarbon (HC)-based fuels to fuel cell equipped vehicles in 10- to 20-year period.[5] Despite the development and research in electric vehicles, problems such as low energy density and insufficient infrastructure limit the wide use of this technology, and hence dependency on internal combustion engines will remain in near future.[6] According to the European Environment Agency (EEA) report, percentage of electric vehicle usage in fleet has only reached 0.04% despite all the investments and incentives.[1] Hydrogen can be produced by conversion from fossil fuels or biomass and electrolysis or direct thermochemical solar conversion methods.[5]

Additionally, when produced from renewable energy sources, hydrogen can be called as a clean fuel, also it can be used as energy transporter such as electricity.[7,8] On the other hand, hydrogen cannot be classified as a wide-range commercial product yet due to lack of filling infrastructure and conservation difficulties.

Several researchers have integrated hydrogen in homogeneous charge compression ignition (HCCI) engines, but narrow operation range and difficulty in controlling the start of combustion limit the commercial usage.[9,10]

In spark ignition (SI) engine studies, hydrogen usage resulted with almost 30% power reduction and several combustion-related problems such as early ignition, knock and back-flame.[11] In spite of high thermal efficiency and less specific CO_2 emissions of diesel engines, high NO_x and smoke emissions are considered as disadvantages.[12,13] After-treatment systems are being used to reduce NO_x and PM of diesel vehicles to predetermine regulation levels and hence such systems (catalysts, selective catalyst reduction (SCR), lean NO_x-trap (LNT), diesel particulate filter (DPF), etc.) cause extra costs.

Hydrogen can be adapted to diesel engines as additional fuel to be an alternative solution to fulfil aforementioned emission regulations.[5] High self-ignition point of hydrogen fuel (576°C) prevents its direct usage in diesel engines.[7] Hydrogen fuel needs an igniter energy source to overcome this drawback.[14] Ikegami et al.[14] used a special glow-plug equipped gas injector to provide ignition of hydrogen, while Antunes et al.[15] heated the intake air for ease of ignition. The literature offers several methods and technologies on injecting hydrogen into intake port using gas injectors, direct injection into engine cylinders, introduction into intake manifold and pilot diesel injection for ignition.[16–18]

Permanent hydrogen injection into intake manifold can cause early ignition and back-flame conditions. During both permanent injection and intermittent port injection methods, hydrogen replaces the intake air during intake stroke due to its low density and causes reduction in volumetric efficiency which results in a decrease in engine power.[19]

Temperature-resistant high pressure gas injectors should be used in direct hydrogen injection method, which are not commercially available. Additionally, modifications on cylinder head must be implemented to locate the gas injectors which limit the commercial use of direct injection method. From this point of view, intake port injection of hydrogen and ignition with diesel fuel method called as dual-fuel method are the most appropriate applications in diesel engines.[4,8]

Hydrogen has superior properties compared to diesel fuel such as high flame speed, wide-range ignition limits, narrow flame extinction region and high diffusion coefficient.[14,20] Using hydrogen in diesel engines as dual fuel provides lower PM emission due to a more homogeneous charge.[21] It can be easily concluded that the reduction in CO_2, CO, HC and PM emissions is more prominent than HC fuels.

HW Wu and ZY Wu[18] investigated 0% and 20% hydrogen addition and exhaust gas recirculation (EGR) rates simultaneously. Test engine was a direct injection diesel engine and the operation conditions were set to constant speed. According to the findings, thermal efficiency increased with hydrogen rate and the brake-specific fuel consumption (BSFC) increased with the EGR rate. In addition, NO_x emission increased with hydrogen content, but authors declared that the increase was controlled by the EGR rate. PM and CO emissions were decreased.

Christodoulou and Megaritis[16] introduced hydrogen and nitrogen into a supercharged engine. Authors operated engine at 2.5 bars and 5 bars of mean effective pressure at 1500 and 2500 r/min engine speeds, respectively. According to the findings, smoke and CO emissions significantly reduced with hydrogen addition while NO_x emissions increased. Thermal efficiency of the engine slightly reduced at low speeds, while an increase was observed at high engine speeds.

In Pan et al.'s[17] study, a two-stroke, supercharged MTU/Detroit 12V-71 TI diesel engine was used. Authors introduced hydrogen at flow rates of 0, 22 and 220 cl/min. Emissions were investigated by the authors at idle and four different operation conditions. According to the results, at full load condition effect of 22 cl/min, the flow rate of hydrogen is negligible on CO_2 and NO_x emissions, while 220 cl/min flow rate of hydrogen results in 1.16% increase in CO_2, 11% reduction in PM emissions and considerable decrease in CO emissions.

Bika et al.[5] investigated the effect of 40% energy equivalent hydrogen introduction to a Volkswagen turbocharged direct injection (TDI) engine with two different fuels. Authors focused on PM and NO_x emissions and used regular diesel fuel and soybean methylester. Authors declared that the hydrogen introduction with regular diesel fuel reduced PM up to 50%, while NO_x emission did not alter significantly.

Miyamoto et al.[6] investigated the effect of hydrogen addition on emission and combustion characteristic. Authors facilitated a single-cylinder direct injection diesel engine. Researchers increased the rate of hydrogen fuel up to 16% simultaneously with late diesel fuel injection which was after top dead centre (TDC). Thanks to this method in-cylinder pressure increase rate and NO_x emission of the engine were limited. In addition, unburned HC emission of the engine was kept identical, while NO gas emission was decreased.

Another important study by Saravanan and Nagarajan[11] focused on the method of hydrogen introduction. Authors implicated three different introduction methods which were port injection, manifold injection and carburettor methods. A single-cylinder direct injection Kirloskar AV1 diesel engine was equipped. Different load conditions with constant 1500 r/min engine speed were determined as operation condition by the researchers. According to results, no considerable difference was observed between port injection and manifold injection. With carburettor method, NO_x emission increased 8% and thermal efficiency and smoke decreased 5% and 8%, respectively. With port injection method, authors declared 18% smoke reduction, 17% and 34% increase in thermal efficiency and NO_x, respectively.

There are numerous studies in the literature that offers effect of hydrogen addition on diesel engine's performance and emission outputs, but less of them focus on the effect of engine speed and hydrogen rate simultaneously on emission and combustion characteristics. Meanwhile, most of the studies indicate CO, CO_2 and smoke emission decrease with hydrogen addition although variation at NO_x and total hydrocarbon (THC) emissions and BSFC especially at part load conditions still remains unclear. In this study, hydrogen was introduced into intake port using a gas injector with the rates of 0%, 25% and 50% of total energy content. Engine speed was set to 750, 900, 1100, 1400, 1750 and 2100 r/min at full load conditions. Engine performance, tail-pipe emissions and combustion characteristics were investigated comprehensively. The work is one of the most comprehensive experimental studies which includes brake power, brake torque, excess air ratio, volumetric efficiency, BSFC, brake thermal efficiency, carbon monoxide, carbon dioxide, THCs, oxides of nitrogen, smoke, exhaust gas temperature, in-cylinder pressure and rate of heat release results depending on hydrogen energy content at different engine speeds. Also, different from the studies in the literature, a self-developed electronic control unit (ECU) was used to control hydrogen injector in the experimental study.

Materials and methods

Details of test bench

A single-cylinder, four-stroke, water cooled, naturally aspirated diesel Cooperative Fuel Research (CFR) engine was equipped for the tests. Engine's compression ratio was set to 19:1 and remained constant.

Engine dynamometer was a direct current (DC) generator which creates magnetic field to break the engine. A controller was integrated on the dynamometer that generates excitation current to alter the load. Engine load was measured by a load cell. Details of the test engine and the dynamometer are listed in Table 1.

Inducted air mass was measured by inclined manometer with a purpose-built orifice. Consumed diesel fuel was measured simultaneously by a turbine-type flowmeter and gravimetric method. Sika branded VZ 0.2 type flowmeter was used. Engine coolant inlet and outlet temperatures and exhaust gas temperature were measured by K-type thermocouples.

Schematic of test system can be seen in Figure 1. Thermal mass flowmeter was used for hydrogen flow measurement which is New-Flow branded and TLF 23 type. NI USB 6215-type data acquisition device was used to log the load cell, diesel fuel mass flow, hydrogen mass flow and emission measurements.

Hydrogen fuel system

Schematic drawing of the hydrogen supply line is depicted in Figure 2. Hydrogen storage was provided by high pressure tubes at 200 bars which further be reduced to 4 bars using a pressure regulator. Before introducing into test engine's intake manifold, a check-valve and a flame arrester were located behind the gas

Table 1. Specifications of the test bed and engine.

Engine manufacturer	Ferryman four-stroke CFR engine
Aspiration	Natural
Number of cylinders	1
Bore × stroke (mm)	90 × 120
Cylinder volume (cm^3)	799
Compression ratio	19 (adjusted for this study)
Swept volume (cc)	765
Maximum brake power (kW)	6.4 kW (1800 r/min/23:1)
Speed range min-max (r/min)	600–2100
Speed range min-max (r/min)	600–2000
Number of intake and exhaust valves	1 and 1
Cooling type	Water cooled
Dyno type and power (kW)	DC and 7.5

CFR: Cooperative Fuel Research; DC: direct current.

injectors for safety. Therefore, any possible back-fire was prevented:

A safety valve was integrated on hydrogen line which exhausts the hydrogen to outside when line pressure reaches up to 10 bars. A buffer tank was used to minimize the fluctuations and hence the prediction of flow measurement in thermal mass flowmeter was provided.

In order to validate the hydrogen flow measurement of thermal mass flowmeter, a cross-check procedure was applied with a specially built rotameter which was designed for hydrogen at 4 bars and 20°C environment temperature.

Keihin LPG–CNG gas injectors were used for hydrogen injection. Injector was precisely controlled by a self-developed electronic control system which can alter the injection signal length and the start of injection timing with respect to crank angle position. For this study, start of hydrogen injection was set to the start of intake stroke.

In-cylinder pressure measurement

In-cylinder pressure was measured with Kistler 6061B type pressure transducer and charge amplifier. Pressure signal instantly monitored and saved by LeCroy oscilloscope at 2Gs/s sampling rate. On an average, 100 consecutive cycles were used in combustion analysis to eliminate cycle-by-cycle variations. Piston and crankshaft position were determined by an encoder located on the crankshaft which is also logged by the oscilloscope.

Krieger and Borman's[22] rate of heat release model was used to analyse combustion parameters in this study.

Exhaust emission measurements

Gaseous emissions were measured with AVL DiCom 4000 which are CO, CO2, NO$_x$ and THC. Smoke measurements were taken by AVL 415S as filter smoke number. AVL DiCom 4000 is a volumetric gas measurement device which is able to determine the

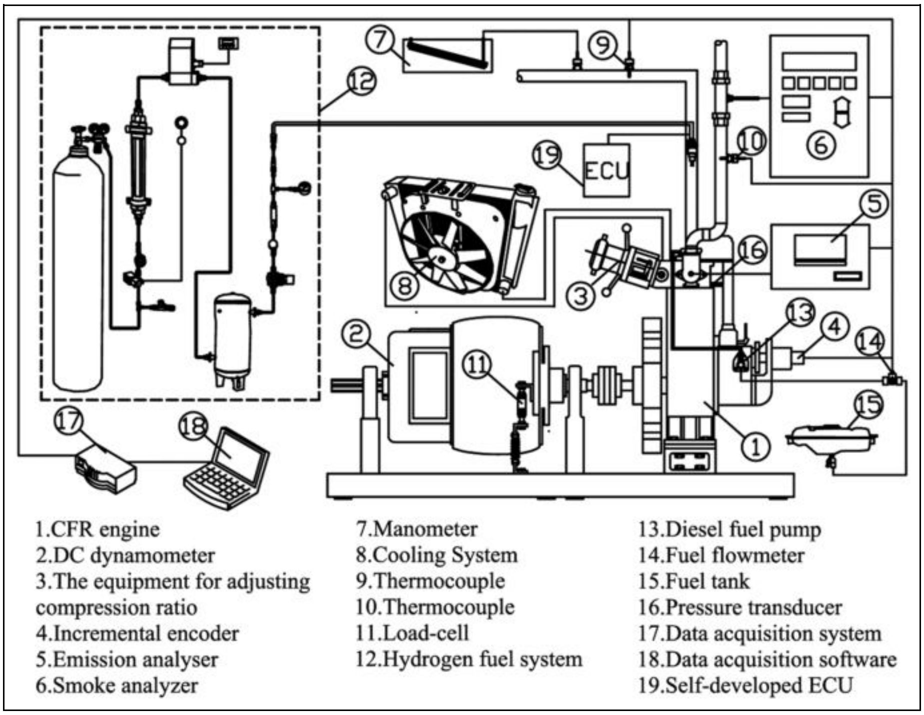

Figure 1. Schematic view of the test bench.

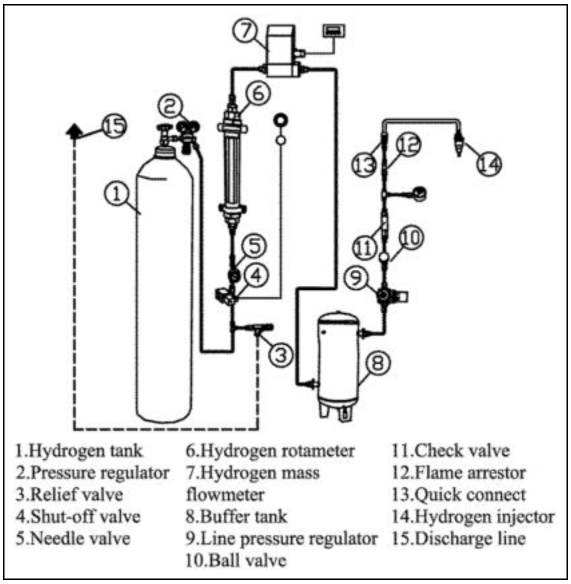

Figure 2. Schematic diagram of the hydrogen fuel system.

Table 2. Test conditions.

Engine speed (r/min)	H_2 energy content (%)	Diesel fuel energy content (%)	Diesel fuel injection advance (CAD before TDC, degrees)	H_2 injection advance (CAD before TDC)
750	0	100	22	At TDC
750	25	75	22	At TDC
750	50	50	22	At TDC
900	0	100	22	At TDC
900	25	75	22	At TDC
900	50	50	22	At TDC
1100	0	100	22	At TDC
1100	25	75	22	At TDC
1100	50	50	22	At TDC
1400	0	100	22	At TDC
1400	25	75	22	At TDC
1400	50	50	22	At TDC
1750	0	100	22	At TDC
1750	25	75	22	At TDC
1750	50	50	22	At TDC
2100	0	100	22	At TDC
2100	25	75	22	At TDC
2100	50	50	22	At TDC

CAD: computer-aided design; TDC: top dead centre.

percentage of CO and CO_2 gas amounts in exhaust, also NO_x and THC emission values are monitored as ppm unit. Meanwhile, smoke measurements with AVL 415S are given as filter smoke number and/or mg/m^3 unit. In this study, hydrogen and diesel fuel combustion and interaction of both fuel types with each other were investigated, and for this reason obtaining comparable results was critical and hence all the emission measurements were converted to brake-specific values according to Verband Deutscher Maschinen- und Anlagenbau (VDMA) exhaust emission regulation.

Experimental procedure

Hydrogen used in this study was 99.99% purity and provided by Linde Group. Diesel fuel was EN590 convenient regular product. Fuel injection advance of the test engine was 22° crank angle before TDC, and also hydrogen injection advance was set to the start of intake stroke. Engine load was set to full load condition and speed was altered as 750, 900, 1100, 1400, 1750 and 2100 r/min. The engine map was generated and brake-specific diesel fuel consumption values were obtained depending on engine load and engine speed in pre-engine tests. Then, hydrogen energy fraction is calculated easily using lower heating values of diesel and hydrogen fuels. Using obtained injection amount of hydrogen injector depending on injection duration, the injected hydrogen fuel amount by injector was easily adjusted. The injection duration of LPG injector was changing between 4 and 12 ms depending on engine speed and hydrogen energy fraction. The hydrogen mass flow rate varies between 12.5 and 44.6 slpm and depends on engine speed and introduced hydrogen energy fraction. Hydrogen rate in mixture was set as 25% and 50% of total energy content. Details of test conditions are listed in Table 2. Total uncertainty was calculated according to the Kline and McClintock[23] method and listed in Table 3.

Results and discussion

Engine brake power, brake torque, excess air ratio, volumetric efficiency, thermal efficiency, BSFC, CO, CO2, THC, NO_x, smoke emissions and exhaust gas temperature data were evaluated to discuss the effect of hydrogen fuel rate. Hydrogen energy rate in total charge was limited to 50% to prevent back-flame which was determined during preliminary experiments. The rate of hydrogen that satisfies the safe operation can be increased by making design enhancements on intake system; however, this is not the scope of this study.

Figure 3(a) shows the variation of brake power generated by test engine at different hydrogen quantities (0%, 25% and 50% hydrogen energy content) based on engine speed. Figure 3(b) shows the variation of brake torque generated by test engine at different hydrogen quantities (0%, 25% and 50% hydrogen energy content) based on engine speed. In Figure 3(c), excess air ratio value was held as close as possible. Hydrogen injection into intake manifold reduces the amount of air inducted by the engine. As seen in Figure 3(d), volumetric efficiency of the test engine was lower through entire engine speed range in 25% and 50% hydrogen

Table 3. Accuracies of the measurements and the uncertainties in the calculated results.

Measured parameter	Measurement device	Accuracy
Engine torque	Load cell	± 0.05 N m
Engine speed	Incremental encoder	± 5 r/min
Diesel flow rate	Sika VZ 0.2	± 1% (of reading)
H_2 flow rate	New-Flow TLF 23	± 1% (F.S.)
CO	AVL DiCom 4000	0.01% vol.
CO_2	AVL DiCom 4000	0.1% vol.
HC	AVL DiCom 4000	1 ppm
NO_x	AVL DiCom 4000	1 ppm
Smoke	AVL 415S	0.4% vol.
Calculated results		Uncertainty
Power		± 0.43%
BSFC		± 1.10%–1.49%

BSFC: brake-specific fuel consumption; HC: hydrocarbon.

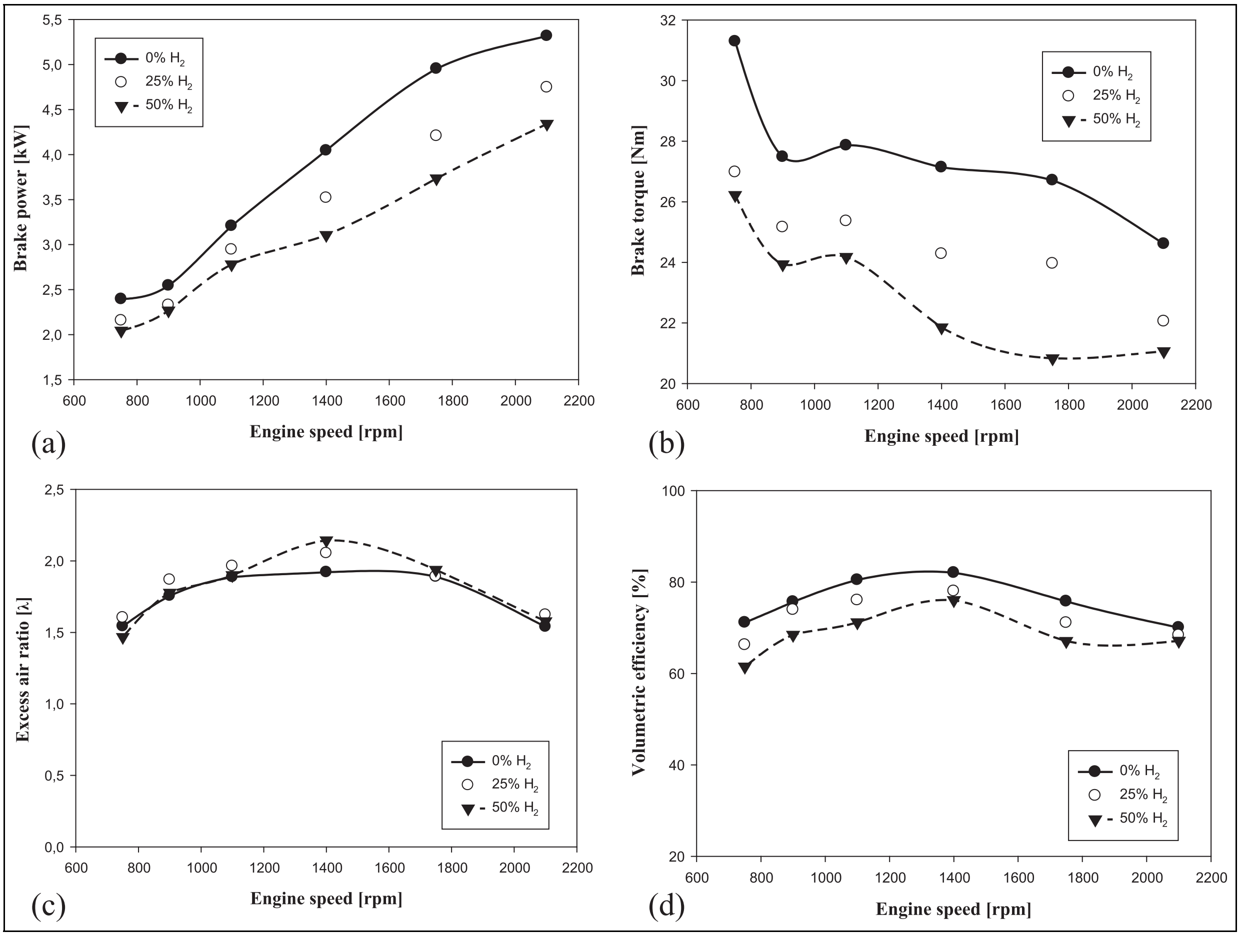

Figure 3. (a) Variation of brake power, (b) brake torque, (c) excess air ratio (d) and volumetric efficiency depending on engine speed and hydrogen rate.

injection experiments. Lower heating value of hydrogen is higher than diesel fuel, but the decrease in volumetric efficiency reduced the torque and hence the power produced by the engine.

Measured loss in engine power is between 8.1% and 15.1% through entire speed range for 25% energy equivalent hydrogen injection. Power output of the test engine decreased much more in 50% energy equivalent hydrogen injection, and results were 10.8% to 25.4% lower compared to neat diesel operation. A decrease in 8.1%–15.1% is seen in brake engine power value with 25% hydrogen addition (as energy basis) and a decrease

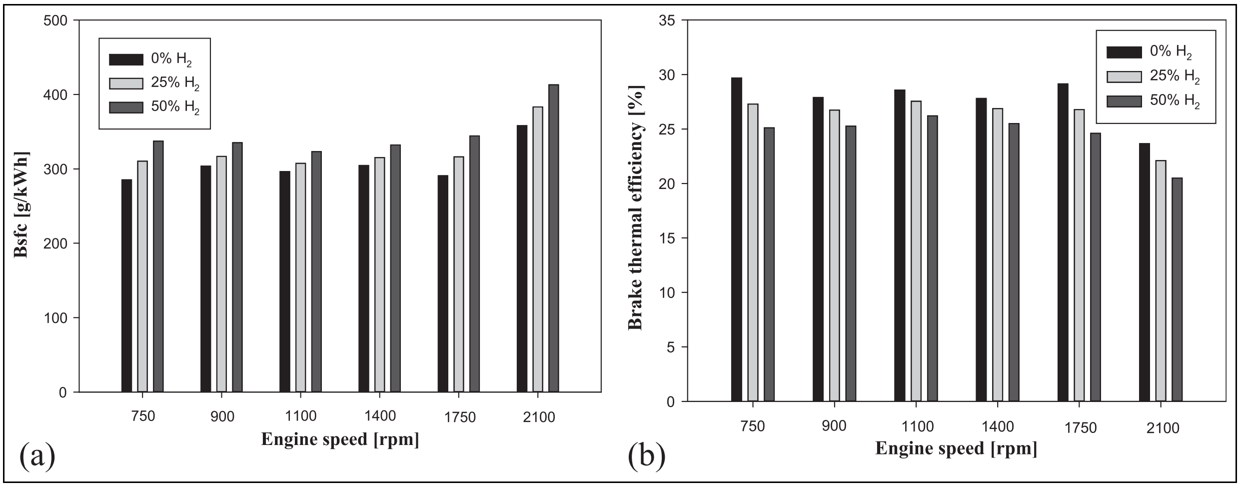

Figure 4. (a) Brake-specific fuel consumption value variation at different hydrogen quantities based on engine speed and (b) brake thermal efficiency value variation at different hydrogen quantities based on engine speed.

in 10.8%–25.4% is seen with 50% hydrogen addition compared to only diesel fuel (0% hydrogen). A decrease in 8.4%–13.7% is seen in brake engine torque value with 25% hydrogen addition (as energy basis) and a decrease in 12.9%–19.4 % is seen with 50% hydrogen addition compared to only diesel fuel (0% hydrogen). Brake engine torque and brake engine power values decreased in parallel with engine speed increase. Excess air ratio value decreased by 6.4% with 25% hydrogen addition and by 9.7% with 50% hydrogen addition compared to only diesel fuel. Volumetric efficiency value decreased by 2.3%–6.8% with 25% hydrogen addition and by 4.1%–13.5% with 50% hydrogen addition compared to only diesel fuel.

BSFC value variation based on engine speed at different hydrogen quantities is shown in Figure 4(a), and brake thermal efficiency value variation based on engine speed at different hydrogen quantities is depicted in Figure 4(b). Hydrogen's flame speed is nine times faster than diesel fuel.[24] With 25% hydrogen addition (energy content of total fuel), a decrease in 3.3%–8.1% is observed in brake thermal efficiency value and a decrease in 8.2%–15.5% is observed with 50% hydrogen addition compared to only diesel fuel condition. BSFC and equivalent diesel fuel quantity obtained from hydrogen's lower specific value are added to consumed diesel fuel quantity and results are found in terms of diesel fuel. With 25% hydrogen addition (energy content of total fuel), an increase in 3.4%–8.7% is witnessed in BSFC value and an increase in 9.0–18.4% is witnessed with 50% hydrogen addition in BSFC value compared to only diesel fuel condition. Normally, diesel fuel combustion with hydrogen increases combustion efficiency.

Since combustion phase advance changes with hydrogen addition, negative impact on thermal efficiency is stated in study of Varde and Frame.[25] Christodoulou and Megaritis[16] mentioned that thermal efficiency decreased at low speeds in their study made on a Ford Puma diesel engine. Experimentally obtained decrease in combustion efficiency of hydrogen is seen as its reason. Hydrogen's higher molar thermal capacity in comparison with N_2 dilutes cylindrical gas (in various studies, N_2 is used to simulate EGR) and consequently decreases combustion efficiency.[17] Hydrogen addition increases heat flux which causes thermal losses according to study of Owston et al.[25]

CO emission value variation based on engine speed at different hydrogen quantities is depicted in Figure 5(a). CO emissions decrease drastically at all engine speeds with 25% and 50% hydrogen addition compared to only diesel fuel condition. An improvement of 20.4%–65.3% and 48.5%–66.3% is seen, respectively, with hydrogen addition corresponding to 25% and 50% of total fuel as energy content compared to only diesel fuel condition (0% hydrogen). All values measured in terms of carbon monoxide do not meet emission regulations. But, percentage values determined via obtained measurements with diesel fuel + hydrogen usage cannot be considered as certain because AVL DiCom 4000 device can measure with 0.01% volumetric accuracy and measurement values of device stay under measurement lower limit in this study. Lower values that cannot be measured by device could be obtained with hydrogen addition so these values could increase. Hydrogen's high flame speed causes increase in cylindrical pressure and an improvement in combustion efficiency. Due to hydrogen's high diffusion coefficient, a more homogeneous ignitable mixture is formed before combustion and oxygen's reachability increases.[27] This fact explains decrease in CO emissions.

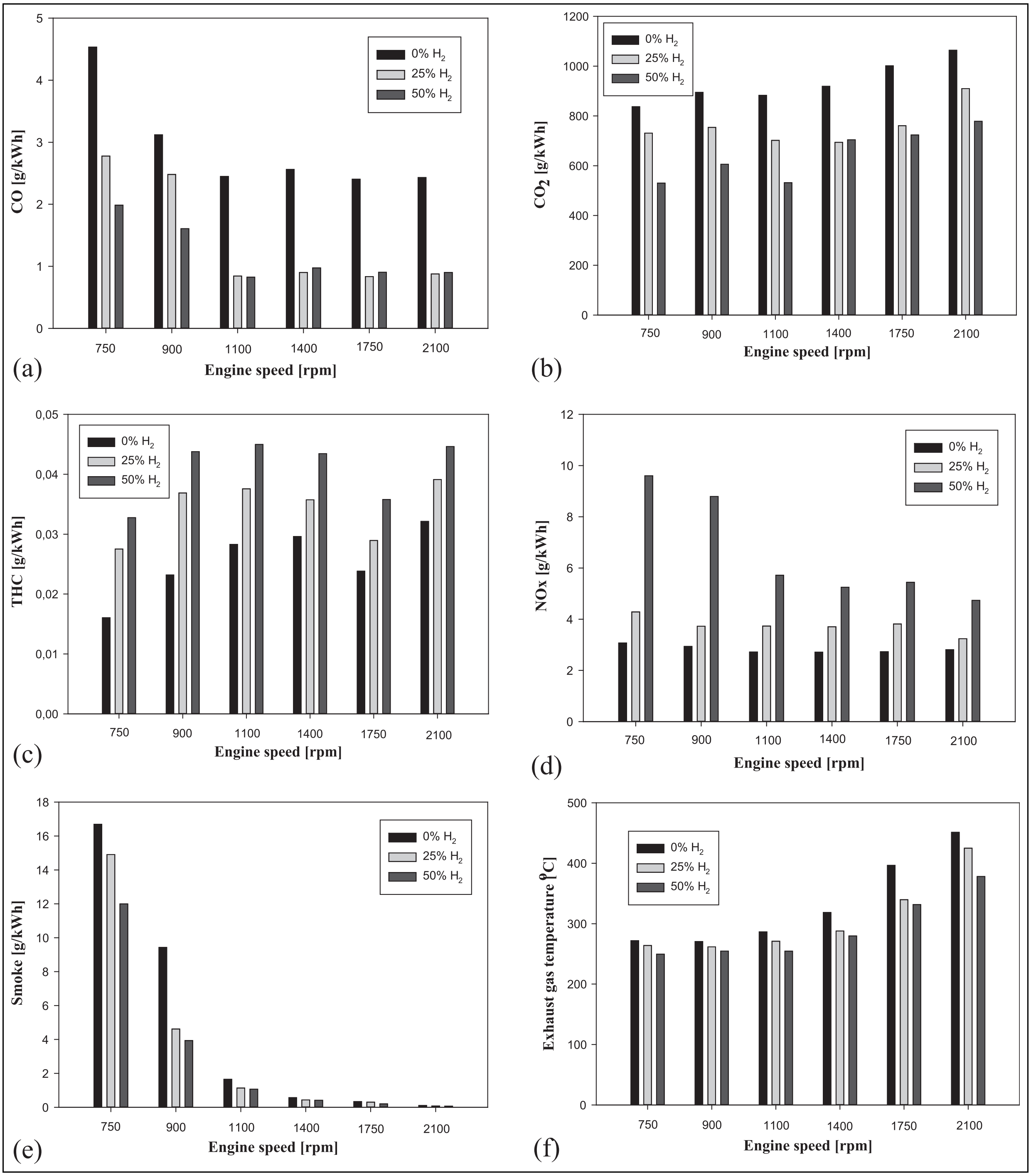

Figure 5. (a) CO emission value variation, (b) CO_2 emission value variation, (c) THC emission value variation, (d) NO_x emission value variation, (e) Smoke emission value variation and (f) exhaust gas temperature value variation based on engine speed at different hydrogen quantities.

CO_2 emission value variation based on engine speed at different hydrogen quantities is depicted in Figure 5(b). CO_2 emissions ameliorate substantially with hydrogen addition at all engine speeds compared to only diesel fuel condition. An improvement of 12.7%–25.4% is seen in CO_2 emissions with 25% hydrogen addition and an improvement of 23.4%–38.7% with 50% hydrogen addition compared to only diesel fuel condition. CO_2 emission decreases since hydrogen contains no carbon.[28] Depending on increase in H/C rate in total fuel with hydrogen addition, combustion duration shortens and combustion efficiency rises.[26,28] On the other hand, by means of hydrogen's high diffusion coefficient, heterogeneity of diesel fuel improves and a more uniform pre-mixed ignitable mixture is formed.[10] Departing from all these results, it is understood that specific CO_2 emissions decrease with hydrogen addition.

Unburned HCs in exhaust gas are generally called as THC.[12] THC emission value variation based on engine speed at different hydrogen quantities is depicted in Figure 5(c). In parallel with hydrogen addition, an increase in THC emissions is observed at all engine cycles. An increase in 20.6%–71.5% is investigated where hydrogen constitutes 25% of total fuel as energy content compared to only diesel fuel condition. An increase in 38.8%–104.2% is investigated where hydrogen constitutes 50% of total fuel as energy content compared to only diesel fuel condition. Obtained THC values are at quite low values according to regulations, accrual in THC emissions with diesel fuel + hydrogen usage is negligible. Obtained results are parallel with results of studies done by Zhou et al.[29] and HW Wu and ZY Wu.[18]

NO_x emission value variation based on engine speed at different hydrogen quantities is depicted in Figure 5(d). NO_x emissions increase with hydrogen addition at all engine speeds compared to only diesel fuel and especially with 50% hydrogen addition NO_x emissions increase drastically. An increase between 15.2% and 39.6% is observed with 25% hydrogen addition and an increase in 68.6%–212.7% is seen with 50% hydrogen addition compared to only diesel fuel. NO_x formation is related with cylindrical gas temperature, oxygen concentration and reaction duration.[19] At normal conditions, an increase in cylindrical peak temperatures and NO_x emissions is expected during hydrogen–diesel fuel combustion.[28]

Smoke emission value variation based on engine speed at different hydrogen quantities is depicted in Figure 5(e). Specific soot emission values decrease at all engine speeds with hydrogen–diesel fuel usage. Referring to obtained results, an improvement between 10.4% and 51.1% is observed with 25% hydrogen addition and an improvement between 28.1% and 58.2% is observed with 50% hydrogen addition at all engine speeds compared to diesel fuel. Either H/C rate increase in total fuel[4] or homogeneity increase in ignitable mixture due to high diffusion coefficient and higher accessibility of fuel to oxygen[10,27] reduces soot emission formation.

Exhaust gas temperature value variation based on engine speed at different hydrogen quantities is depicted in Figure 5(f). Exhaust gas temperature value decreases with hydrogen addition at all engine speeds. A decrease between 2.9% and 14.3% with 25% hydrogen addition and a decrease between 5.8% and 16.3% with 50% hydrogen addition is investigated at all engine speeds compared to diesel fuel. Hydrogen's flame speed is known to be higher than diesel fuel. Due to hydrogen's high flame speed, exhaust gas temperature decreases; thus, exhaust heat loss released with exhaust gases reduces.

In-cylinder pressure value variation depending on crank angle at 0%, 25% and 50% energy contents is shown in Figure 6(a) for 750 r/min engine speed, in Figure 6(b) for 900 r/min engine speed, in Figure 6(c) for 1100 r/min engine speed, in Figure 6(d) for 1400 r/min engine speed, in Figure 6(e) for 1700 r/min engine speed and in Figure 6(e) for 2100 r/min engine speed. At all engine speeds, cylindrical pressure value increases in parallel with hydrogen rate in stated graphics. Referring to obtained results, peak cylindrical gas pressure increases by 1.5%–11.1% with 25% hydrogen addition and by 13.1%–34.7% with 50% hydrogen addition compared to only diesel fuel. Fast burning of hydrogen due to its high flame speed raises both pressure increase rate[4] and also peak pressure values reached after combustion. According to obtained results, a more explosive-type combustion occurs because of hydrogen's high flame speed. Acquired results (Figure 7) are parallel with Christodoulou and Megaritis.[16]

Heat release rate value variation depending on crank angle at 0%, 25% and 50% energy contents is shown in Figure 6(a) for 750 r/min engine speed, in Figure 6(b) for 900 r/min engine speed, in Figure 6(c) for 1100 r/min engine speed, in Figure 6(d) for 1400 r/min engine speed, in Figure 6(e) for 1700 r/min engine speed and in Figure 6(e) for 2100 r/min engine speed. During diesel fuel combustion, classical diesel combustion phases are investigated; but during diesel fuel + hydrogen combustion, an explosive-type non-controllable combustion phase is seen due to hydrogen's high flame speed.[4] Although knocking possibility is extremely high during non-controllable combustion phase where in-cylinder homogeneous hydrogen existence causes a superior pressure variation according to crank angle with diesel + hydrogen usage, no knocking is observed in this study since hydrogen's energy content is limited with 50% of total fuel. According to obtained results, maximum heat release rate value increases by 28.4%–42.8% with 25% hydrogen addition, while maximum heat release rate value increases by 64.7%–84.6% with 50% hydrogen addition compared to only diesel fuel. Because of homogeneous hydrogen existence in cylinder before ignition, hydrogen has more effect on non-controllable combustion phase. Acquired results are in phase with Saravanan and Nagarajan.[11]

Conclusion

In this study, the effect of 25% and 50% hydrogen addition on performance, emissions and combustion characteristics at full load and 750, 900, 1100, 1400, 1700, 2100 r/min engine speeds is investigated.

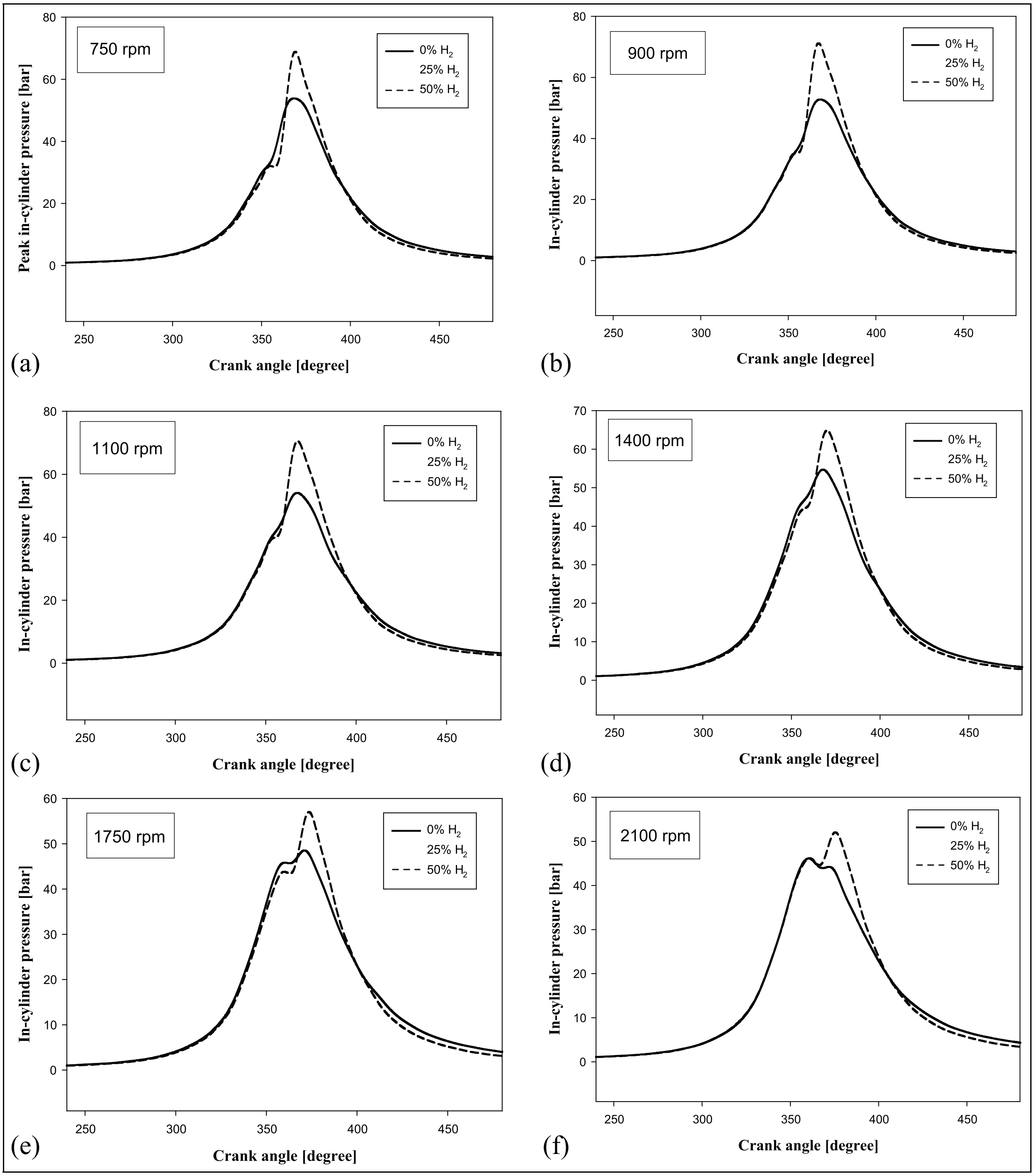

Figure 6. In-cylinder pressure value variation depending on crank angle at different hydrogen quantities for (a) 750 r/min engine speed, (b) 900 r/min engine speed, (c) 1100 r/min engine speed, (d) 1400 r/min engine speed, (e) 1700 r/min engine speed and (f) 2100 r/min engine speed.

Acquired results are listed below:

1. Brake engine power value decreases by 8.1%–15.1% with 25% hydrogen addition (as energy basis) and by 10.8%–25.4% with 50% hydrogen addition compared to only diesel fuel (0% hydrogen). Brake engine torque and volumetric efficiency values have also decreased compared to only diesel fuel (0% hydrogen). By holding excess air ratio value as close as possible, hydrogen may be taken in cylinder instead of some air.

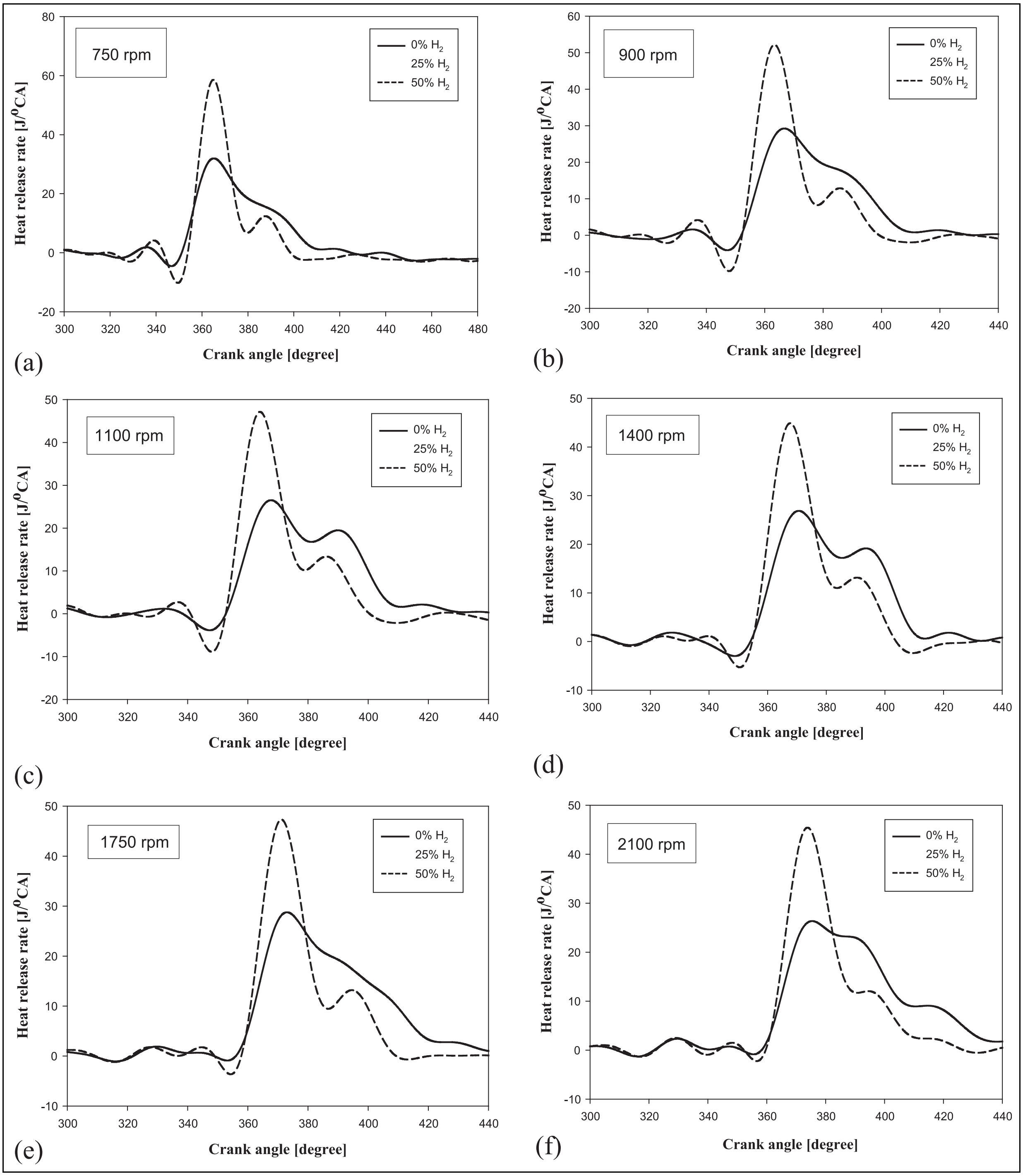

Figure 7. Heat release rate value variation depending on crank angle at different hydrogen quantities for (a) 750 r/min engine speed, (b) 900 r/min engine speed, (c) 1100 r/min engine speed, (d) 1400 r/min engine speed, (e) 1700 r/min engine speed and (f) 2100 r/min engine speed.

2. Brake thermal efficiency value decreases by 3.3%–8.1% with 25% hydrogen addition (as energy content of total fuel) and by 8.2%–15.5% with 50% hydrogen addition compared to only diesel fuel. BSFC and equivalent diesel fuel quantity obtained from hydrogen's lower specific value are added to consumed diesel fuel quantity and results are found in terms of diesel fuel. BSFC value increases with hydrogen addition at all cycles.
3. Similarly, hydrogen enrichment of filling causes a drastic decrease in CO emissions at all engine

speeds. An improvement of 20.4%–65.3% and 48.5%–66.3% is observed, respectively, with 25% and 50% hydrogen addition as energy content of total fuel compared to only diesel fuel (0% hydrogen). Moreover, CO_2 value decreases with hydrogen addition at all engine speeds.

4. Soot emissions decrease drastically at all cycles with diesel + hydrogen addition. An improvement of 10.4%–51.1% is seen with 25% hydrogen addition and of 28.1%–58.2% with 50% hydrogen addition at all engine speeds compared to diesel fuel.
5. By increasing hydrogen addition, dramatic rise of NO_x emissions could not be prevented. NO_x emissions increase by 15.2%–39.6% with 25% hydrogen addition and by 68.6%–212.7% with 50% hydrogen addition compared to diesel fuel.
6. Maximum cylindrical pressure and maximum heat release rate values increase at all engine speeds with hydrogen addition. Peak cylindrical gas pressure rises by 1.5%–11.1% with 25% hydrogen addition, while it rises by 13.1%–34.7% with 50% hydrogen addition compared to diesel fuel. Maximum heat release rate values increase by 28.4%–42.8% with 25% hydrogen addition and by 64.7%–84.6% with 50% hydrogen addition compared to diesel fuel.

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