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COMBUSTION CHARACTERISTICS OF A DIESEL-HYDROGEN DUAL FUEL ENGINE

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ABSTRACT

Among the alternative fuels, hydrogen shows great potential in the near future. In the present study, hydrogen utilization as diesel engine fuel was investigated. Hydrogen can not be used directly in a diesel engine due to its autoignition temperature higher than that of diesel fuel. One alternative method is to use hydrogen in enrichment or induction. To investigate the combustion characteristics of this dual fuel engine, a single cylinder diesel research engine was converted to utilize hydrogen as fuel. Hydrogen was introduced to the intake manifold using a mixer before entering the combustion chamber. The engine was run at a constant speed of 2000 rpm and variable loads. At each load step the flow rate of hydrogen was varied. Fuel consumption, injector needle lift movement, and cylinder pressure were measured. Introducing hydrogen to the combustion chamber reduced the diesel fuel consumption. Indicated efficiency slightly increases with hydrogen enrichment at 15 Nm load. At lower load the efficiency decreases. Specific energy consumption increases with increase in hydrogen flow rate at 5 and 10 Nm load. Inversely, it decreases at higher load. Cylinder pressure decreases with hydrogen enrichment at 5 and 10 Nm, but slightly increases at higher load

***Keywords**:* diesel, hydrogen, dual fuel, combustion

INTRODUCTION

Development of new energy resources has become important agenda in relation to national energy policy. Efforts have been delivered to utilize those energy resources strategically, including intensification, diversification, and conservation. Alternative fuels such as alcohol, gas (CNG, LPG, biogas, producer gas, and hydrogen) have been studied intensively. Among those alternative fuels, hydrogen shows great potential. The advantages of using hydrogen as fuel for internal combustion engine is amongst other a long-term renewable and less polluting fuel, non-toxic, odorless, and has wide range flammability. Other hydrogen properties that would be a challenge to solve when using it for internal combustion engine fuel, i.e.: low ignition energy, small quenching distance, and low density (Fulton et al., 1993). Hydrogen can not be used directly in a diesel engine because its autoignition temperature is higher than that of diesel fuel. One alternative method is to use hydrogen in enrichment or induction. Hydrogen is mixed with air or injected in the intake manifold before entering combustion chamber. Small amount of diesel fuel, called pilot fuel, is injected to promote ignition. This "dual fuel" engine, or is often called "diesel pilot-ignited hydrogen engine" has the advantage to switch back to conventional diesel operation in case of shortfall in gas supply. These benefits lead researchers worldwide investigated the utilization of gas including hydrogen as fuel for diesel engine.

The diesel-hydrogen dual fuel engine can be operated with less fuel than neat diesel operations, resulting in lower smoke level. This H_2-enriched system enables the realization of higher brake thermal efficiency hence specific energy consumption (SEC). NO_x emissions were also reduced except at full load operation (Saravanan and Nagarajan, 2008a). Hydrogen induction particularly when its energy share increased above 15% resulted in sharp decrease in ignition delay, very high peak pressure rates, increase in smoke and loss in fuel efficiency (Pundir and Kumar, 2007). The brake thermal efficiency of dual fuel with exhaust gas recirculation (EGR) is higher than that of neat diesel operation. Using EGR slightly decreased the efficiency. Dual fuel operation without EGR resulted in the lowest smoke and unburned HC. EGR reduced NO_x emission effectively (Saravanan et al., 2008). It was found that CO, FSN, and THC increase with EGR but NOx emission decrease drastically. Inversely, CO, FSN, and THC emission decrease with hydrogen, but NOx increases. This inverse relationship will allow the combination of EGR and hydrogen induction to be optimized to minimize both FSN and NOx (McWilliam et al., 2008). Another way to introduce hydrogen into the combustion chamber is by injecting the hydrogen into the intake port, while diesel fuel was injected directly inside the cylinder. Using port-injected hydrogen there was an increase in brake thermal efficiency of the engine with a greater reduction in emissions (Saravanan et al., 2007b). Any decrease of emission, especially NOx is likely due to enhancement of turbulent mixing in cylinder caused by the injection of pressurized hydrogen through the intake valve (Lilik et al., 2010). Timed manifold injection (TMI) of hydrogen gave higher thermal efficiency and avoided undesirable combustion (Saravanan and Nagarajan, 2008b; Saravanan and Nagarajan, 2010; Saravanan et al., 2007a). Hydrogen induction with TMI coupled with EGR results in lowered emission level and improved performance level compared to the case of neat diesel operation (Bose and Maji, 2009)

The role and benefit of hydrogen in a modern common rail turbocharged automotive diesel engine has been reported. Hydrogen substation yields modest emission reductions with limited penalty on engine performance. The practicality of vehicle utilizing hydrogen substitution is limited by the equipment cost versus the cost benefit from the modest emission reduction (Lilik et al., 2010). Although research on hydrogen combustion in internal combustion engine has intensified, the number of published papers in the field of hydrogen-diesel co-combustion is not as rich as for hydrogen used in spark ignited engines (Szwaja and Grab-Rogalinski, 2009). The objective of this work is to identify benefit of hydrogen enrichment on the diesel combustion process in a stationary diesel engine. To that end, experiments were performed to investigate the combustion process of diesel-hydrogen dual fuel engine. The in-cylinder pressure traces and rate of heat release characteristic will be used to validate the phenomenological combustion model which was still being developed.

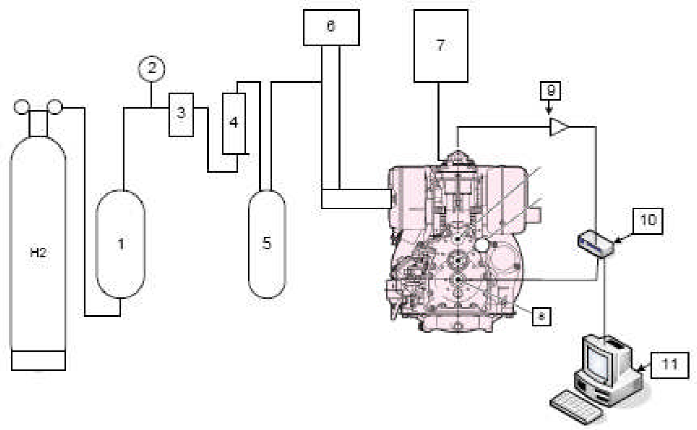
METHODOLOGY

A single cylinder diesel engine with the specifications as shown in Table 1 was converted to utilize hydrogen as fuel. Hydrogen was introduced to the intake manifold by a mixer before entering the combustion chamber. It was supplied from a high-pressure cylinder (150 bar) and then reduced to a pressure of 1.5 bar using a pressure regulator. Hydrogen was passed through a fine control valve to adjust the flow rate and then through a gas flow meter that metered the flow of hydrogen. The hydrogen was passed through a flash back arrestor (flame arrestor) preventing reverse flow of hydrogen into the system. Next, the hydrogen was allowed to pass through a flame trap, used to suppress flash-back into the intake manifold.

Table 1: Engine Specifications

Engine Type	Single cylinder air-cooled DI diesel engine
Rated power	10.3 kW @ 3000 rpm
Maximum torque	36 Nm @ 2000 rpm
Bore x stroke	100 mm x 85 mm
Conrod length	136.5 mm
Swept volume	0.667 liter
Compression ratio	20.5:1

Figure 1 shows the schematic of the experimental setup. The engine was coupled to a SCHENCK make eddy-current dynamometer with a rated power of 70 kW. Engine torque and speed were measured by the dynamometer. In-cylinder pressure was measured using a Kistler water-cooled piezo electric pressure transducer and was sampled every 1 degree crank angle. Start of injection and injection duration were measured by a needle lift sensor. Pressure traces and needle lift data were recorded and analyzed using an engine indicating system. Diesel fuel consumption was measured using gravimetric fuel balance AVL 733S. Hot film anemometer was used to measure air consumption.



1. Hydrogen surge tank
2. Barometer
3. Digital gas flow meter
4. Flash back arrestor
5. Flame trap
6. Hot film air flow meter
7. Gravimetric fuel meter
8. Crank angle encoder
9. Signal conditioning
10. Engine indicating system
11. PC

Figure 1: Schematic of the experimental setup

The engine was run at a constant speed of 2000 rpm and variable load of 5 Nm, 10 Nm, and 15 Nm. At each load the hydrogen was introduced at the flow rate of 21.4, 28.5, 36.2, 42.8, and 49.6 liter/minute. The engine was started with diesel fuel at 2000 rpm and 5 Nm load. After allowing the engine to reach the steady state conditions, the following parameters were measured and recorded: fuel (diesel and hydrogen) consumption, air consumption, exhaust gas temperature, needle lift, and cylinder pressure. Hydrogen was introduced at the flow rate of 21.4 liter/minute; engine speed was kept constant by adjusting the injection pump lever position. The above parameters were measured and recorded again. This procedure was repeated for different loads and hydrogen flow rates.

RESULTS AND DISCUSSION

In this investigation, the combustion characteristics of a DI diesel engine are studied by using hydrogen enrichment. The percentage of diesel energy at each load condition when hydrogen was introduced is depicted in Figure 2. As expected, part of diesel fuel was replaced by hydrogen. Hydrogen was introduced at the same flow rate increment for each load condition. Hence, at the same hydrogen flow rate the percentage of diesel fuel is higher for a higher load.

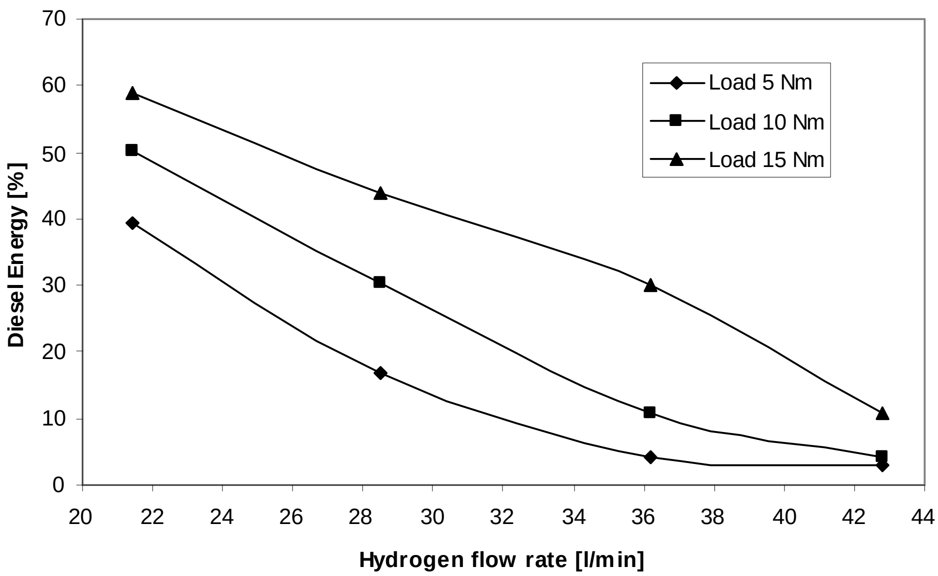


Figure 2: Diesel energy replacement by hydrogen

Figure 3 shows the response of diesel injector when hydrogen was introduced at 2000 rpm and 5 Nm. The reduction of diesel fuel was represented by the injector needle lift over the crank angle. Start of diesel injection is almost the same for all condition. Diesel reduction is shown by a smaller distance of needle lift and the earlier end of injection. Figure 4 depicts the variation in specific energy consumption (SEC) at each load for different level of hydrogen enrichment. SEC indicates the amount of total fuel energy (diesel and hydrogen) needed to produce 1 kW power for an hour engine operation. It means that a lower SEC indicates higher engine efficiency. SEC increases with an increase in hydrogen at low load operation. At higher load, SEC tends to decrease slightly with an increase in hydrogen. This is due to the premixing of hydrogen fuel with air due its high diffusivity and uniform mixing with air resulting in improved combustion (Saravanan and Nagarajan, 2008a).

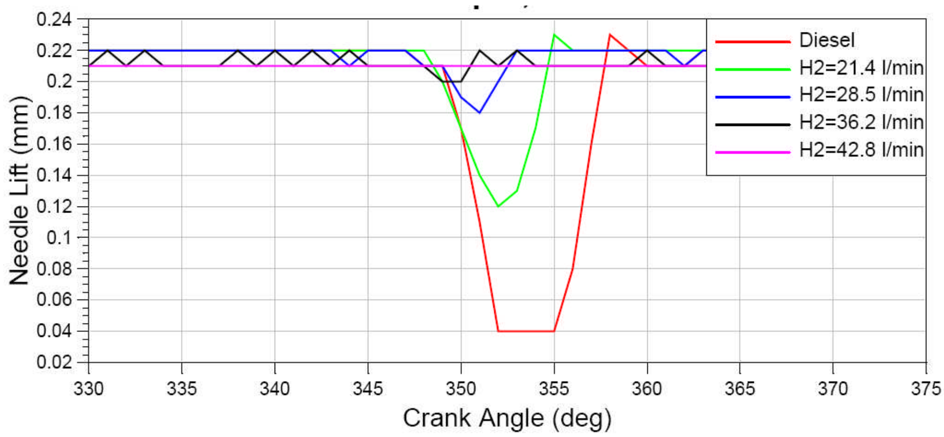


Figure 3: Needle lift at 2000 rpm, 5 Nm

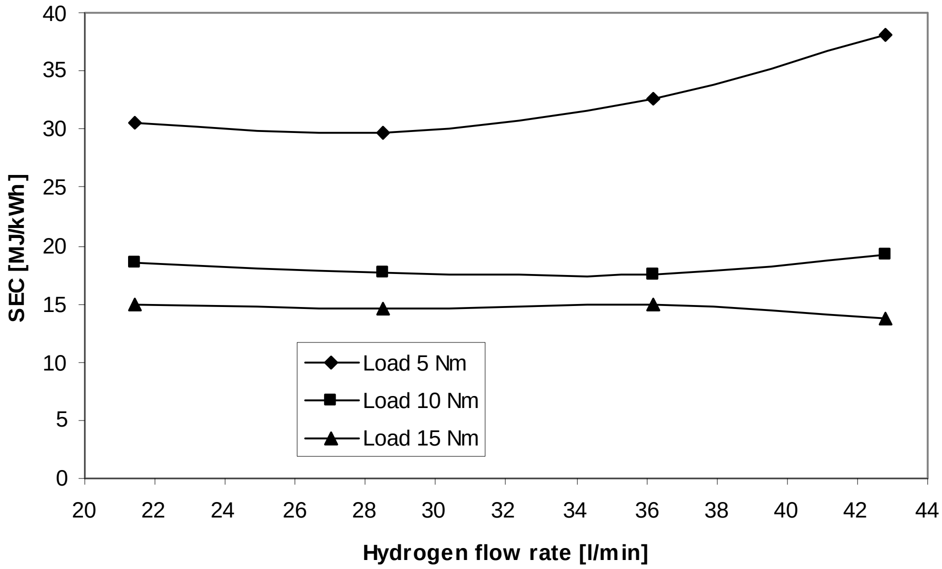


Figure 4: Variation of SEC with hydrogen enrichment

Figure 5 shows the variation of indicated efficiency at each load when hydrogen was introduced. It relates the indicated power to the supplied fuel energy. Higher load resulted in higher indicated efficiency. It means that the combustion efficiency is better at higher load. The efficiency at 15 Nm load slightly decreases with an increase in hydrogen supply up to 36.2 l/min, and then the value increases. Inversely, at lower loads the efficiency decrease. This condition affects the values of SEC shown in Figure 4.

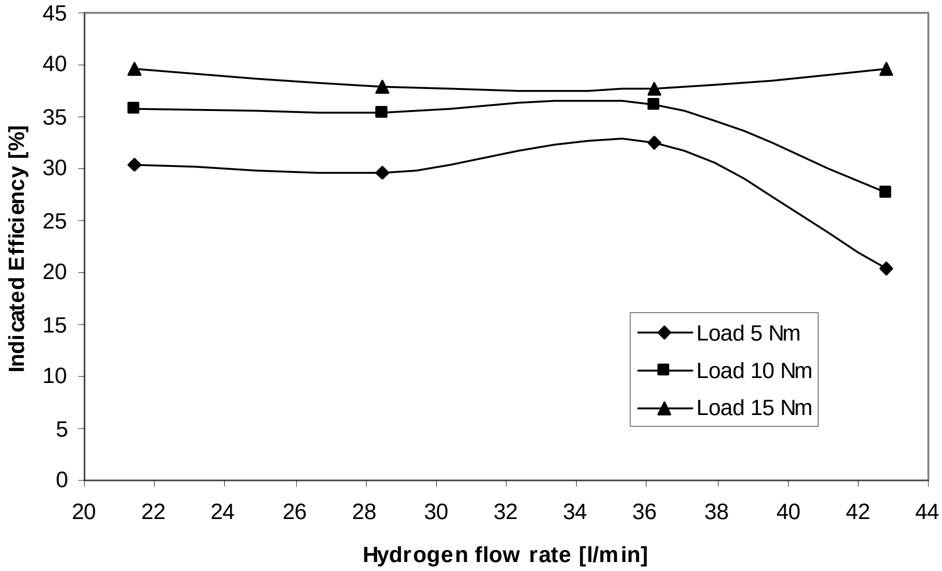


Figure 5: Variation of indicated efficiency with hydrogen enrichment and load

Effect of Hydrogen Enrichment on Combustion

The variation of cylinder pressure traces at speed 2000 rpm and 5 Nm load for different hydrogen flow rate is shown in Figure 6. It is noted that hydrogen addition will reduce the cylinder peak pressure and the pressure rise. More hydrogen enrichment resulted in lower cylinder pressure. The combustion process was promoted by the autoignition of diesel fuel. In such a lower load, diesel percentage on energy basis reduced significantly with an increase in hydrogen. The amount of diesel fuel to ignite the premixing of hydrogen with air was reduced and resulted in a late start of combustion. Part of diesel-type premixed combustion was also reduced as shown in rate of heat release diagram in Figure 7.

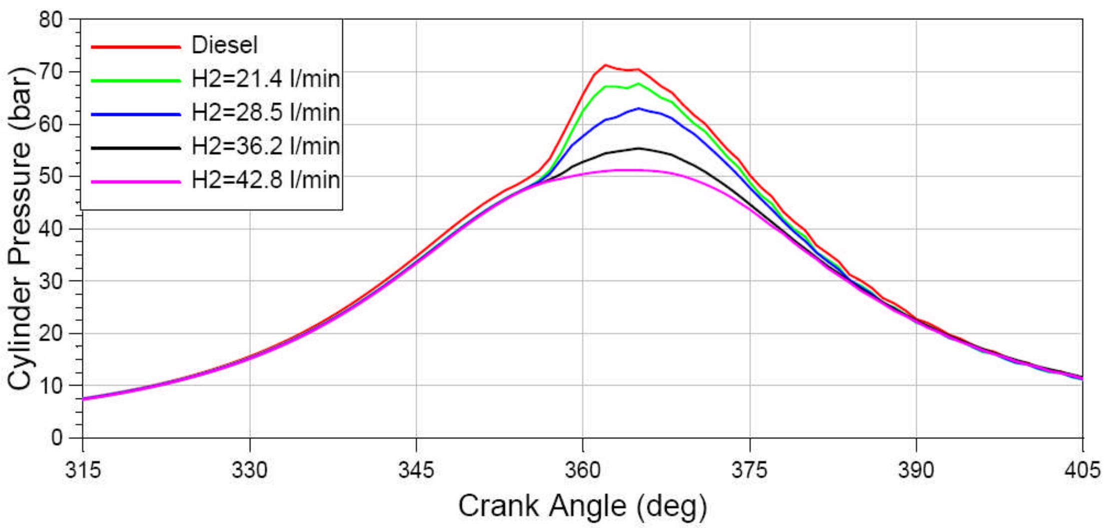


Figure 6: Cylinder pressure at 2000 rpm and 5 Nm

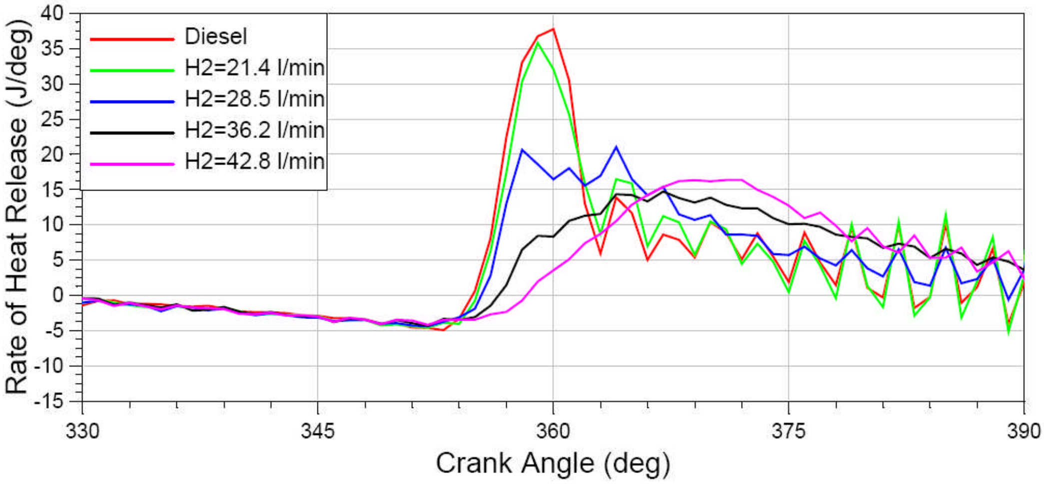


Figure 7: Rate of heat release at 2000 rpm, 5 Nm

Figure 8 depicts the pressure traces at engine operating condition of 2000 rpm and 10 Nm. There is no significant peak pressure reduction when hydrogen was introduced up to 28.5 l/min. The pressure rise is almost the same with that of diesel combustion. Further increasing hydrogen flow rate reduced both peak cylinder pressure and pressure rise significantly. This may be due to the availability of diesel fuel needed to ignite the premixing of hydrogen with air. The percentage of diesel fuel at 21.4 l/min and 28.5 l/min hydrogen enrichment were around 50% and 30% respectively. A further increase in hydrogen enrichment reduced the percentage of diesel fuel to 10.8% and 4.2%. These portions of diesel may not adequate to produce an efficient combustion. The indicated efficiency dropped significantly as seen in Figure 5. Furthermore, the combustion starts a little bit later as shown in Figure 9.

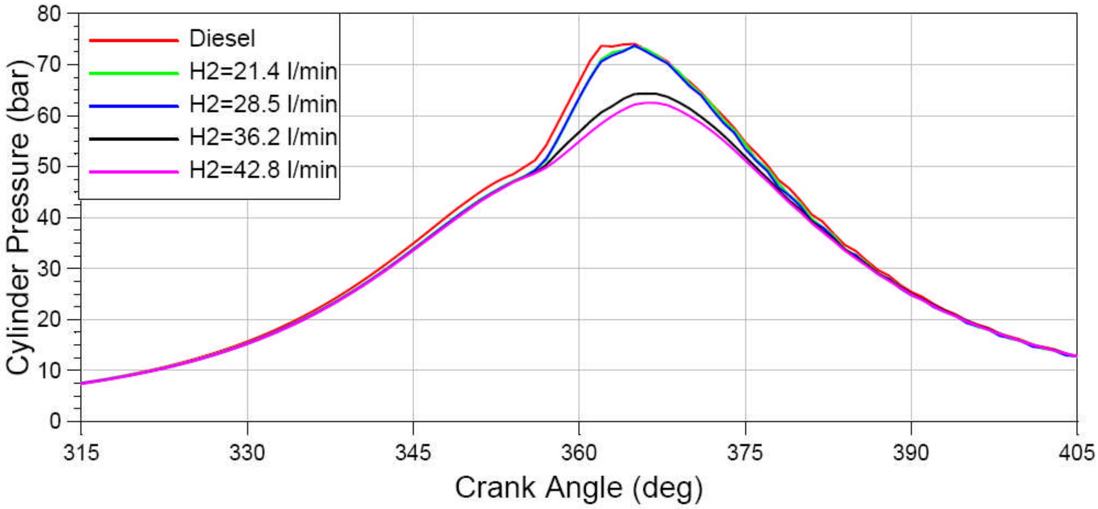


Figure 8: Cylinder pressure at 2000 rpm, 10 Nm

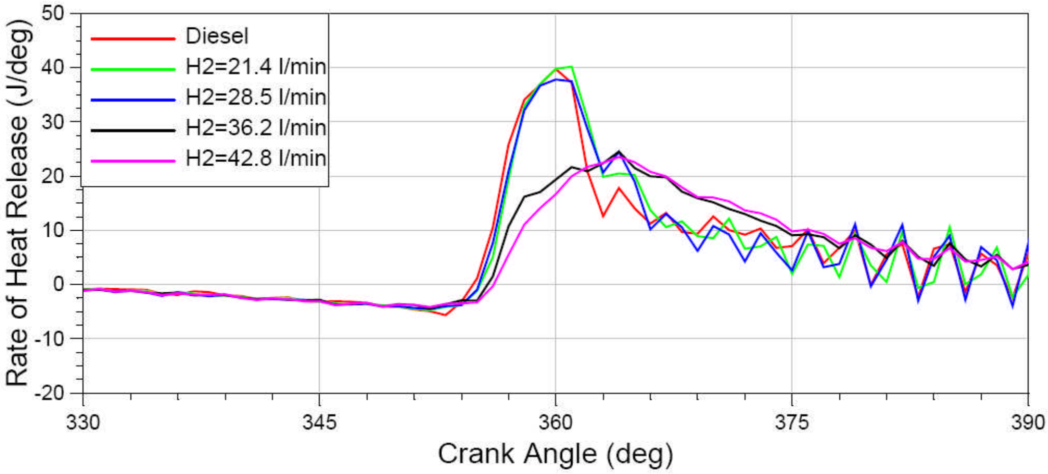


Figure 9: Rate of heat release at 2000 rpm, 10 Nm

Figure 10 shows the variation of cylinder pressure for different level of hydrogen enrichment at engine speed 2000 rpm and 15 Nm load. This is the highest load applied during this investigation. It is noted that the cylinder peak pressures resulted from dual fuel combustion are higher than that of diesel combustion. In this operating condition, the percentage of diesel fuel is more than 10% and indicated efficiency is slightly increased at higher hydrogen flow rate. This portion of diesel fuel may adequate to produce efficient dual fuel combustion. Ignition delay is a little bit longer and most combustion is in the form of premixed combustion. It is shown in Figure 11 that the combustion duration of dual fuel combustion is longer than that of diesel combustion.

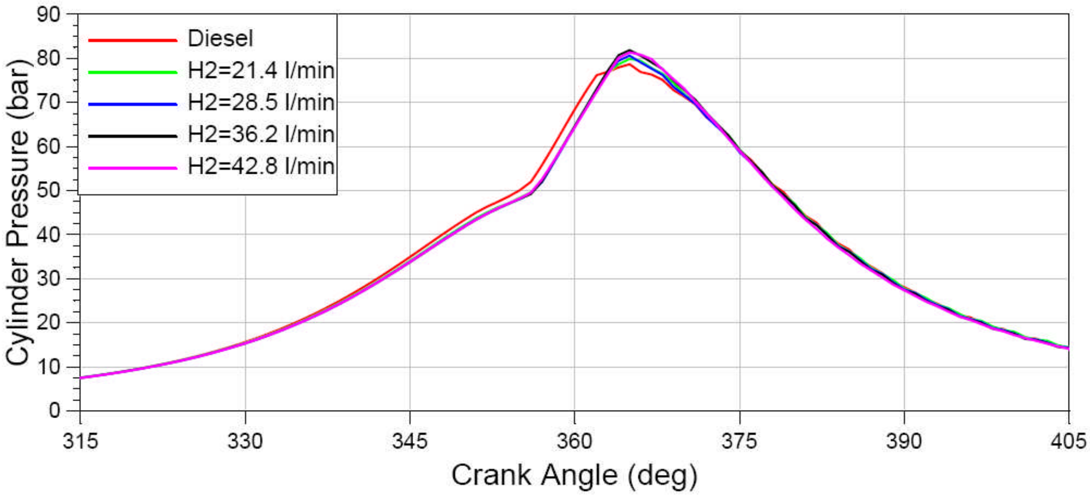


Figure 10: Cylinder pressure at 2000 rpm, 15 Nm

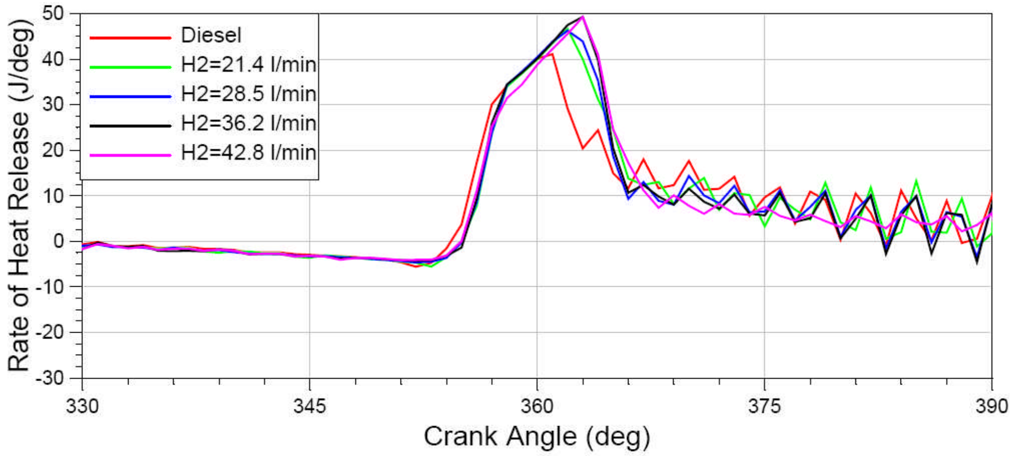


Figure 11: Rate of heat release at 2000 rpm, 15 Nm

CONCLUSION

Based on the experiments conducted on diesel-hydrogen dual fuel engine, the following conclusions can be drawn:

1. The replacement of diesel fuel with hydrogen in DI stationary diesel dual fuel was realized by a shorter injector needle lift movement and an earlier end of injection
2. Indicated efficiency slightly increases with hydrogen enrichment at 15 Nm load. At lower load the efficiency decreases
3. Specific energy consumption increases with increase in hydrogen flow rate at 5 and 10 Nm load. Inversely, it decreases at higher load.
4. Cylinder pressure decreases with hydrogen enrichment at 5 and 10 Nm, but slightly increases at higher load

The investigation needs to be expanded to have a wider range engine operation. Knock could be occurred at higher load and higher hydrogen enrichment. The comparison of emission between diesel and dual fuel will be taken into account. In line with this experimental work, simulation works was conducting to have a better understanding of diesel-hydrogen dual fuel combustion process.

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