# THE EFFECTS OF SMALL AMOUNT OF HYDROGEN ADDITION ON PERFORMANCE AND EMISSIONS OF A DIRECT INJECTION COMPRESSION IGNITION ENGINE

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*In this study, the effects of small amount of hydrogen addition into the intake of compression ignition engine on the performance and emissions characteristics of single cylinder, air cooled, direct injection, compression ignition engine were experimentally investigated. An electrolysis unit was built to produce hydrogen peroxide, which was then fed into the intake manifold of the compression ignition engine. The compression ignition engine was tested with different amount of hydrogen (0.15, 0.30, 0.45 and 0.60 lpm) at different engine load (5%, 25%, 50%, 75% and full load) and the constant speed, 2200 rpm. Experimental results show that increasing amount of hydrogen into the inlet air resulted to decrease in brake specific fuel and energy consumption while resulted to increase brake thermal efficiency at all load conditions due to uniformity in mixture formation and higher flame speed of hydrogen. The better combustion improved exhaust emission. However, exhaust temperature only increased for 0.6 lpm hydrogen addition into the inlet air at higher loads resulting in higher quantity of nitrogen oxides formation.*

Keywords*: Diesel Engine; Electrolysis; Hydrogen; Engine Performance; Exhaust Emissions*

## 1. Introduction

Increasingly stringent emissions legislation on exhaust emissions, unfavorable effects of the emissions on human health and environment, and weakening of worldwide petroleum reserves afford strong encouragement for research on alternative fuels. As an alternative fuel, $H_2$ ($H_2$) has great potential. Clean burning characteristics of $H_2$ and its better performance drives growing interest in $H_2$ such a fuel [1]. The compression ignition (CI) engines fueled with diesel and $H_2$ offers the potential of reduced emissions with improved performance [2]. Addition of $H_2$ can also result in extremely low smoke density (SD) and better thermal efficiency thereby reducing the fuel consumption however with a nominal power loss. Small amount addition of $H_2$ to a CI engine increases the H/C ratio of the entire fuel and decreases heterogeneity of a diesel fuel spray due to the high diffusivity of $H_2$ which makes better combustible mixture. It could also reduce the combustion duration due to its high speed of flame propagation [3-9].

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In an experimental investigation was conducted on a CI engine using port-injected $H_2$ as the primary fuel and direct in-cylinder diesel fuel injection to control ignition, Saravanan et al. [10] reported reductions in both nitrogen oxides (NOx) and SD and increases in brake thermal efficiency (BTE) for dual-fuel operation compared with conventional CI engine operation. Varde and Varde [11] investigated effects of burning gaseous fuels together with diesel fuel in a naturally aspirated direct injection (DI) engine and detected that at light loads, the addition of $H_2$ reduced soot formation up to half of conventional diesel, while NOx increased with increasing $H_2$-to-carbon ratio. Lee et al. studied on $H_2$ mixed with the intake air by using injector [12] and carbureting [13]. Electronic injectors using for $H_2$ have a superior control over the injection timing and injection duration with quicker response under high-speed operating conditions [14]. Elimination of problems like backfire and pre ignition with proper injection timing is the main advantage of $H_2$ injection over carbureted system [15]. In the study conducted by Tomita et al. [16], $H_2$ was mixed with the intake air of a DI-CI engine. It is reported that very low NOx emissions were obtained when start of injection was advanced. As a result of less carbon content in the fuel, it was also observed that hydrocarbon (HC) and carbon monoxide (CO) emissions often reduced [17,18]. An experimental research was employed by Saravanan and Nagarajan [19] on a stationary CI engine to improve performance and emissions. NOx emissions reduced one-fifth of the conventional case up to 90% $H_2$ enrichment at medium engine load. Conversely at full load, NOx emissions increased slightly compared with conventional diesel operation, while SD reduced by about 50%. In another experimental investigation carried out by Saravanan et al. [20] was done on a CI engine using $H_2$ in the dual fuel mode. Experimental results showed an increase in BTE advance up to 30% with a significant reduction in NOx compared with diesel.

However higher NOx emissions that has an undesirable effect on environment is an obvious drawback of $H_2$-operated engines. NOx formation becomes significant when the combustion peak temperature is so high above 2200 K [21,22]. Operating the $H_2$ engine with lean mixtures is one of the ways of reducing NOx while keeping fuel economy better. That results in lower peak temperature that would slower the chemical reaction because of cooler combustion, which weakens the kinetics of NOx formation [23,24]. Using of $H_2$ in dual fuel mode with exhaust gas recirculation (EGR) technique also resulted in lower NOx emissions with lower SD level and particulate matter [25]. The use of EGR is, therefore, believed to be most effective in improving exhaust emissions of $H_2$-operated engines.

The main disadvantage of using $H_2$ as a fuel for automobiles is on-board storage of $H_2$ and $H_2$ supply infrastructures are not available and need to be developed in near future [26,27,28]. One of the viable solutions to this problem is to generate $H_2$ on-board. Small amount of $H_2$ fumigation into the intake of engine by using an electrolysis unit positively affects engine performance and especially emissions. Gjirja et al. [29] was observed a decrease in NOx when small amounts of hydrogen peroxide ($H_2O_2$) were fumigated into the intake of an engine using an electronic injector. Shirk et al. [30] conducted a sets of experiments to investigate the effects of fumigation gaseous $H_2$ to the intake of CI engines fueled with bio-diesel (B20). Results of experiments showed that NOx emissions decreased slightly, exhaust temperature increased slightly, and efficiency changes were small. It can be concluded that $H_2$ fueled engine is not negatively impacted by the fumigation of small amounts of $H_2$.

From the literature review, the influence of small amount of addition $H_2$ into the intake of CI engine on the performance and emissions characteristics of CI engine has not been clearly studied. Therefore, these topics need to be investigated to make up for the deficiency in the literature. For this reason, in the present study, the effects of addition $H_2$ into the intake air of CI engine on the performance and emissions characteristics of single cylinder, air cooled, DI-CI engine were experimentally investigated. An electrolysis unit was built to produce $H_2O_2$, which was then fed into the intake manifold of the CI engine. The CI engine was tested with addition different amount of $H_2$ [0.15, 0.30, 0.45 and 0.60 liter per minute (lpm)] into the intake air at different engine load (5%, 25%, 50%, 75% and full load) and the constant speed, 2200 rpm.

## 2. Experimental Setup

The diesel engine used for the study was a direct injection, single cylinder; four-stroke, air-cooled Lombardini 6 LD 400 engine. Bore and stroke of the engine are 86 mm and 68 mm, respectively. Compression ratio is 18:1. Maximum engine power and torque are 8 kW and 21 N.m, respectively. Fuel injection pressure and timing are 20 MPa and 20° BTDC, respectively. The engine was loaded by an electrical dynamometer rated at 10 kW and 380 V. The load on the dynamometer was measured using a strain gauge load sensor. Accuracy of the load sensor is $\pm 2\,\mathrm{N}$. An inductive pickup speed sensor was used to measure the speed of the engine. Accuracy of the speed sensor is ±2 rpm. The fuel consumption was measured with a burette (10 and 20 ml volumes) and a stopwatch. The exhaust gas, lubricating oil, and air-fuel inlet temperatures were measured by K type thermocouples. Accuracy of the thermocouples is ±1 °C. The $H_2$ was generated by electrolyzing water using an oxygen- $H_2$ generator machine.

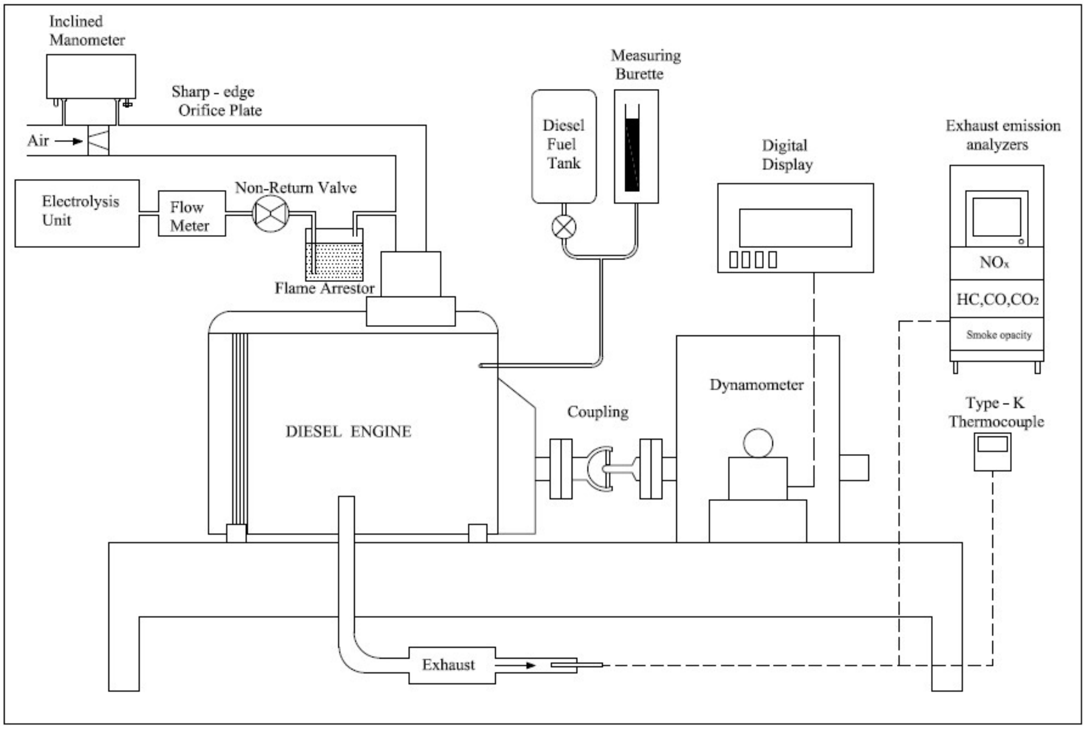

**Fig.1.** Schematic diagram of experimental setup.

The potassium hydroxide (KOH) water solution was used as a conductive electrolyte. By use of this system, the relation between the input voltage, KOH percentage and the produced H2 gas was determined. The generated H2 is then passed through a flow meter before it is introduced to the engine by the use of the air inlet manifold. The H2 was passed through a non-return valve, preventing reverse flow of H2 into the system. A flame arrestor was installed into the H2 line in order to prevent flash-back into the H2-containing system. The H2 from the flame arrestor was allowed inside the inlet manifold with a nozzle. The engine was started on neat diesel fuel and warmed up. The warm up period is assumed to end when the engine reaches the stabilized working condition (when the engine lubricating oil temperature reaches 75±5 °C). The engine was operated at a constant speed of 2200 rpm obtained maximum torque with five different percentage of load (5%, 25%, 50%, 75%, and 100%). Under each load condition, the flow rate of diesel fuel and other parameters were first recorded without any induction of H2 into the engine. Then, with no change in the experimental conditions, a small amount of H2 (0.15, 0.30, 0.45, and 0.60 lpm) was supplied to the intake manifold and the amount of diesel was arranged to obtain desired each load. In this study, the process of mixing air and H2 is called as enrichment air with H2. After allowing the engine to reach steady state conditions for about 10 min, engine parameters such as speed of operation, engine load, diesel fuel consumption, exhaust temperature were collected. Brake power, brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC), and BTE were computed. Uncertainty of BSFC, BSEC and BTE is ±2.60%. Exhaust emissions like carbon dioxide (CO2), CO, HC and NOx were measured using an BOSCH-750 exhaust gas analyzer and SD was measured using a smoke analyzer. Accuracy of CO2, CO, HC and NOx are ±0.001%, ±0.01%, ±1 ppm, and ±1 ppm, respectively. Each reading was replicated thrice to obtain a reasonable value. Schematic diagram of experimental setup is plotted in Fig. 1.

## 3. Results and Discussion

### 3.1. Engine Performance

Addition of $H_2$ into the intake air has a significant effect on the emission characteristics and performance of a CI engine because $H_2$ has excellent combustion, desirable emissions characteristics and other positive features. Therefore, in this study, the influence of $H_2$ addition on engine performance parameters such as BTE, BSFC, BSEC and emission characteristics such as $NO_x$, $CO_2$, CO, HC, SD and exhaust gas temperature (EGT) of a single cylinder diesel engine has been experimentally investigated. The experimental conditions were selected as follows: four engine loads (5%, 25%, 50%, 75% and full load), 2200 rpm constant speed and four different amount of $H_2$ (0.15, 0.30, 0.45 and 0.60 lpm).

#### *3.1. 1. Brake thermal efficiency (BTE)*

The BTE is defined as the ratio of the brake power to fuel consumption and lower heat value (LHV). BTE indicates the ability of the combustion system and provides comparable means of assessing how efficient the energy in the fuel was converted to mechanical output [31]. The variation of BTE with respect to load for different amount of introduced $H_2$ is shown in Fig. 2. Increasing engine load causes to increase in BTE values due to noticeably decline in BSFC for all fuel mixture. At 75% load, the maximum BTE for 0.60 lpm $H_2$ enrichment is 26.29% compared to 25.56% for pure diesel operation. It can be seen from Fig.2. 2,85% improvement is occurred in brake thermal efficiency. At full load, the highest BTE is found to be 23.88% for 0.60 lpm $H_2$ enrichment compared to diesel of 23.21%. The increase in BTE is owing to the uniformity in mixture formation and higher flame speed of $H_2$ assists to have more complete combustion resulting in an improvement in BTE at all load conditions [32]. The best results in terms of BTE were obtained at 0.60 lpm addition of $H_2$.

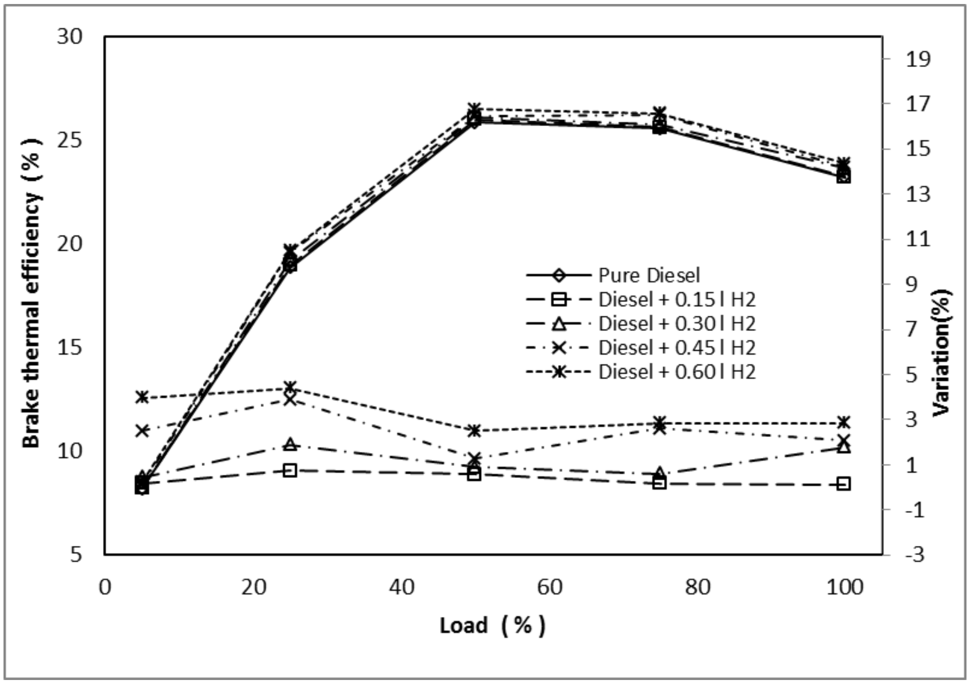

**Fig.2**. Variation of BTE

### *3.1.2. Brake specific fuel consumption (BSFC)*

BSFC is defined as the ratio of the fuel consumption to the brake power [33]. The variation of BSFC with respect to engine load for the neat diesel fuel and the $H_2$ enrichments is presented in Fig. 3a. For all of the fuels, BSFC has the tendency to decrease with respect to increasing of engine load until it reaches a minimum value and then increases a small amount with further increase in engine load. One possible explanation for this decrease could be the higher percentage increase in the brake power with load as compared to fuel consumption.

As shown in Fig. 3a, the BSFC slightly decreased with increasing $H_2$ amount in the inlet mixture because of owing to the uniformity in mixture formation and higher flame speed of $H_2$ leads to better combustion resulting in an improvement in BSFC at all load conditions. At 75% load the minimum BSFC value is acquired 322.18 g/kWh for 0.60 lpm $H_2$ enrichment compared to diesel of 331.35 g/kWh. At full load, the minimum value of BSFC is 354.73 g/kWh at 0.60 lpm $H_2$ flow rate compared to pure diesel 364.88 kg/kWh. On average for all engine loads, BSFC for 0.15, 0.30, 0.45, and 0.60 lpm $H_2$ addition boosted by 0.22, 0.77, 1.72, and 2.44%, respectively, compared to those of pure diesel.

### *3.1.3. Brake specific energy consumption (BSEC)*

The BSEC is described as multiplication of BSFC and LHV [34]. As shown in the Fig. 3b, The BSEC reduces with increasing engine loads because of noticeably diminishing BSFC for the all fuel mixtures. It is also observed from the Fig. 3b that the BSEC for all of the $H_2$ addition conditions is lower than that of diesel. The lowest BSEC of 13.59 MJ/kWh is obtained for 0.60 lpm $H_2$ enrichment compared to diesel of 14.08 MJ/kWh at 75% load. At full load, the BSEC for $H_2$ enriched engine is 15.08 MJ/kWh compared to diesel, which is 15.51 MJ/kWh. The reduction is 2.77% at full load for 0.60 lpm $H_2$ enrichment. The reduction in BSEC is due to better mixing of $H_2$ in addition to assisting diesel during the combustion process [26]. The optimum BSEC was found to be at 0.60 lpm $H_2$ enrichment.

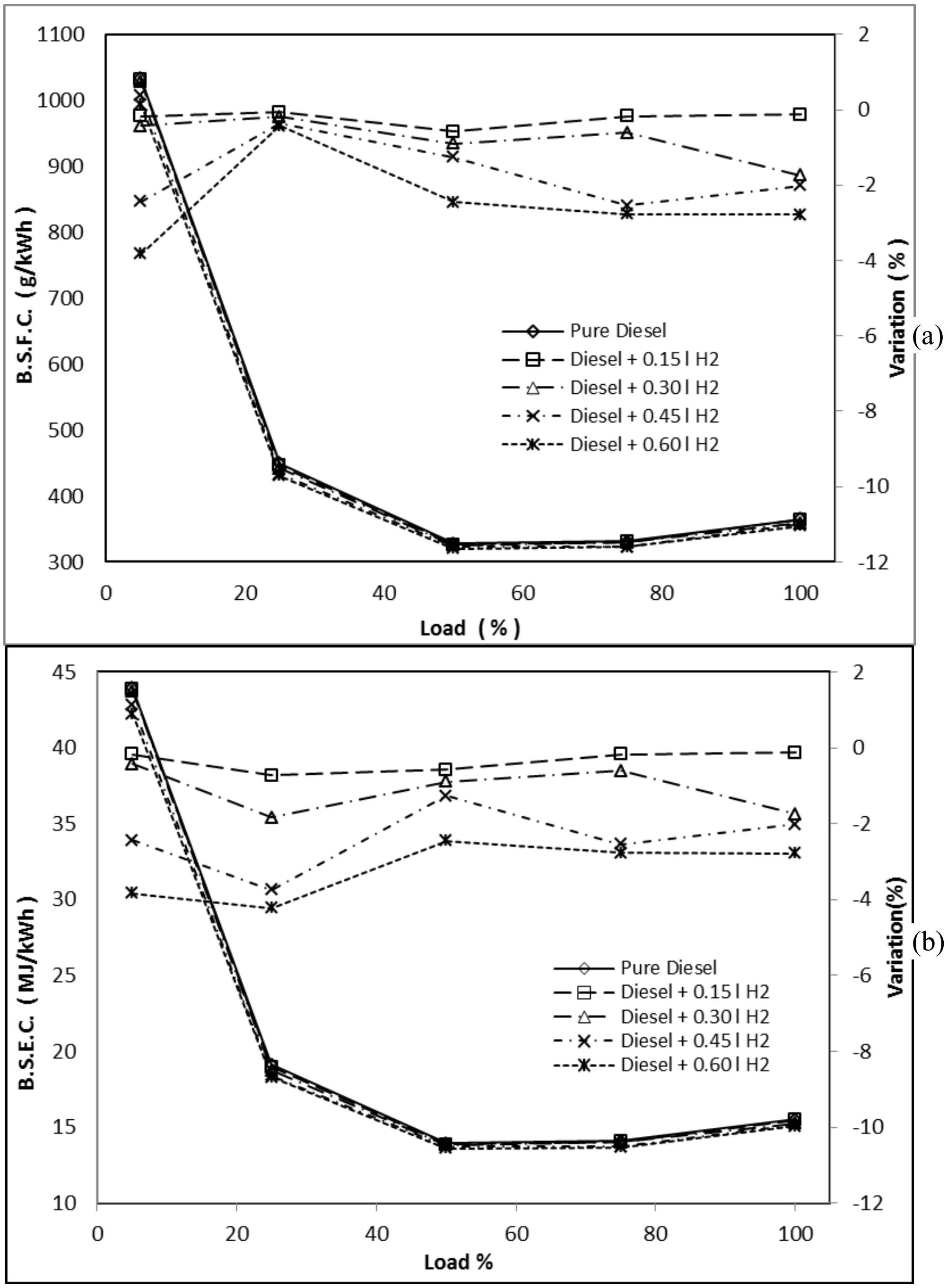

**Figure 3.** Variation of BSFC (a) and BSEC (b)

### 3.2. Exhaust Gas Temperature (EGT)

Fig. 4a depicts the variation of EGT with load. The EGT increases with increase in load. It is observed that the EGT for all $H_2$ enrichment conditions is higher than diesel at full load. At full load the maximum EGT was 599 ºC at 0.60 lpm $H_2$ enriched air mixture compared to diesel of 581 ºC.

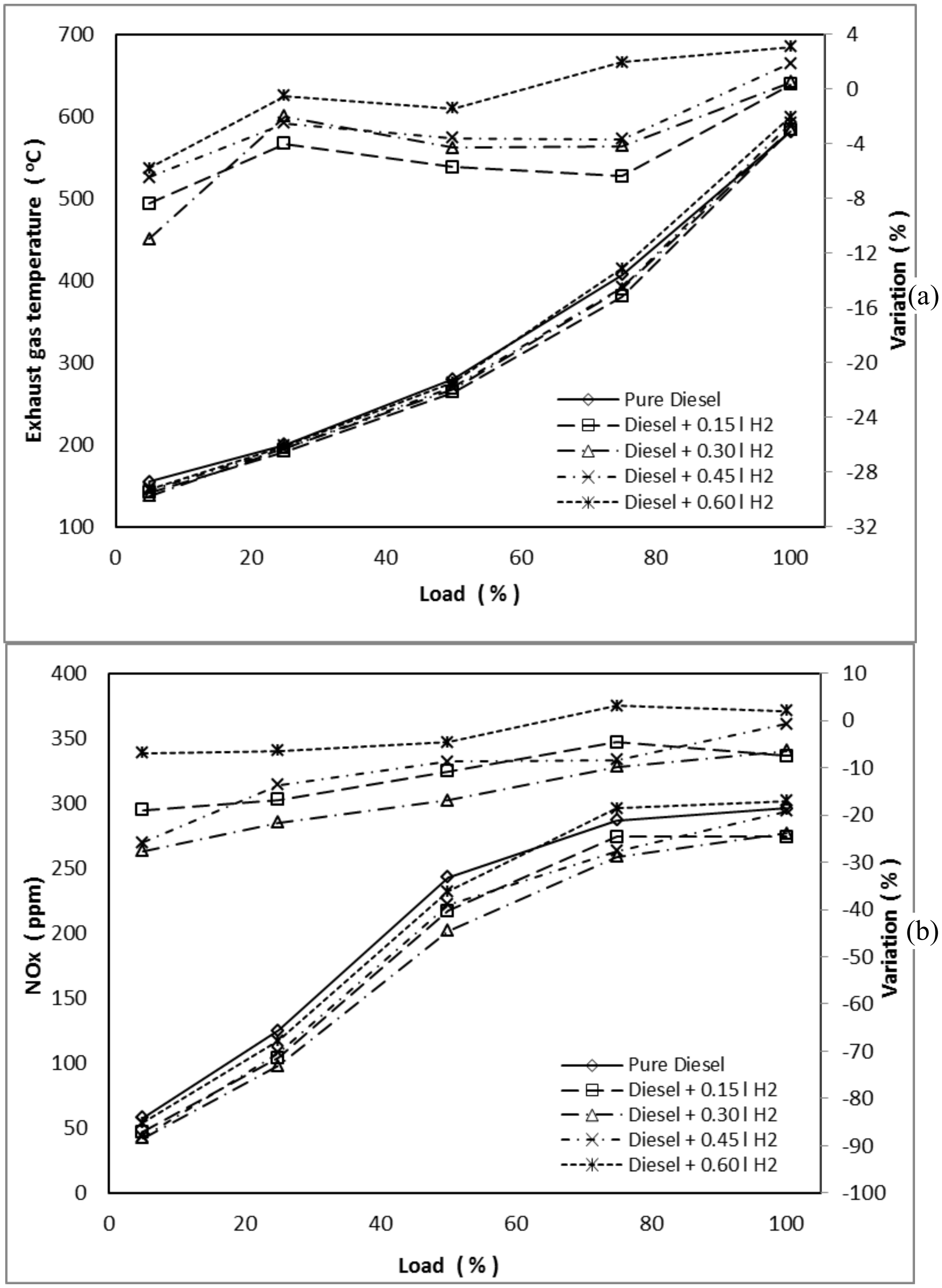

Figure 4. Variation of EGT (a) and $NO_x$ emissions (b)

## 3.3. Exhaust Emissions

### *3.3.1. Nitrogen oxides ($NO_x$)*

The conversion of nitrogen and oxygen to $NO_x$ is generated by the high combustion temperatures occurring within the burning fuel sprays controlled by local conditions. $NO_x$ is collective term used to refer to nitric oxide (NO) and nitrogen dioxide ($NO_2$). $NO_x$ emissions form in the high-temperature burned gas region, which is non-uniform, and formation rates are highest in the close to stoichiometric regions [34]. The variation of $NO_x$ with the engine load for different amount of $H_2$ into the inlet air is presented in Fig. 4b.

$NO_x$ emissions increased with the increasing engine load because of increasing combustion temperature as shown in Fig. 4b. $NO_x$ emissions decreased for all $H_2$ enrichments at lower load condition. However at higher load conditions, $NO_x$ emissions initially decreases slightly with the addition of $H_2$ into the inlet air until it reaches 0.45 lpm value but it increases with more enhancement of the $H_2$ addition owing to better combustion leads to higher temperature resulting in an increase in $NO_x$ emissions. The $NO_x$ emission is found to be high, 296 ppm at 75 percent load for 0.60 lpm $H_2$ enrichment compared to diesel of 287 ppm. At full load for 0.60 lpm $H_2$ enrichment $NO_x$ is found to be 302 ppm compared to diesel of 296 ppm. On average for all engine loads, $NO_x$ emissions for 0.15, 0.30, 0.45, and 0.60 lpm $H_2$ addition decreased by 11.68, 16.44, 11.42, and 2.53% compared to those of pure diesel, respectively.

### *3.3.2. Smoke density (SD)*

Due to the heterogeneous nature of diesel combustion, there is a wide distribution of fuel-air ratios within the cylinder. SD is attributed to either fuel-air mixtures that are too lean to auto-ignite or to support a propagating flame, or fuel/air mixtures that are too rich to ignite. Soot formation mainly takes place in the fuel-rich zone at high temperature and high pressure, especially within the core region of each fuel spray, and is caused by high temperature decomposition [31]. The variation of SD with the engine load for different $H_2$ enrichments is depicted in Fig. 5a. The formation of smoke strongly depends on the engine load. As the load increases, more fuel is injected, and this increases the formation of smoke. The results obtained in this study support this statement.

As seen in Fig. 5a, SD has tendency to decrease with the increasing fraction of $H_2$ into the inlet mixture. At 75% load in the 0.60 lpm $H_2$ enriched condition is observed to be 40.41% compared to diesel of 44.14%. The lowest SD value of 6.29% is observed at 0.60 lpm $H_2$ enrichment at 5% load. $H_2$ forms a homogeneous air-fuel mixture rather than heterogeneous mixture unlike diesel resulting in a further reduction in SD. For all engine loads, SD for 0.15, 0.30, 0.45 and 0.60 lpm $H_2$ addition diminished by 7.74, 16.10, 20.34, and 27.58% compared to those of pure diesel, respectively.

### *3.3.3. Hydrocarbon (HC)*

The variation of HC with engine load for different percent $H_2$ into the inlet mixture is given in Fig. 5b. As shown in the Figure, HC emission was steadily decreased when the amount of $H_2$ increased in the inlet air. This is also due to the uniformity in mixture formation and higher flame speed of $H_2$ leads to better combustion resulting in an improvement in HC emission at all load conditions [35]. At 75% load the HC is 22 ppm for the 0.60 lpm $H_2$ enrichment compared to 40 ppm for diesel. At full load the $H_2$ enrichment results in a decrease in HC emission compared to neat diesel operated engine. For 0.60 lpm $H_2$ operation it is 28 ppm compared to diesel of 45 ppm. On average, HC emissions for all engine loads for 0.15, 0.30, 0.45, and 0.60 lpm $H_2$ addition decreased by 9.09, 16.54, 25.79, and 34.53% compared to those of pure diesel, respectively.

### *3.3.4. Carbon monoxide (CO)*

The CO emissions in the exhaust represent lost chemical energy that is not fully used in the engine. Generally, CO emission is affected by the equivalence ratio, fuel type, combustion chamber design, atomization rate, start of injection timing, engine load, and speed. The most important among these parameters is the fuel type [31].

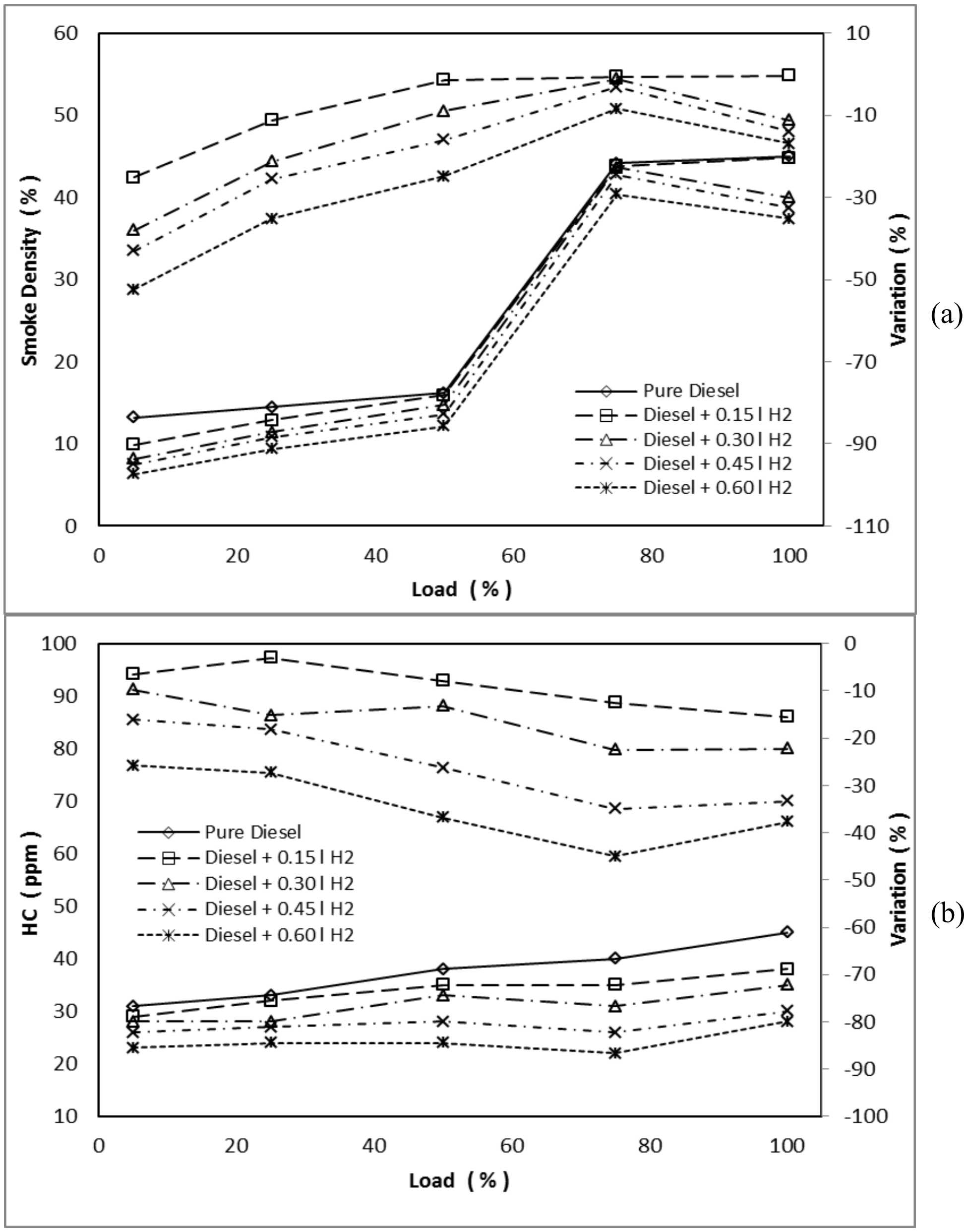

**Figure 5.** Variation of SD (a) and HC (b)

The variation of CO with engine load for the different amount of $H_2$ into the inlet air is presented in Fig. 6a. While the fuels are producing low amount of CO emission at light load levels, those are giving more emissions at high loading conditions. The CO emissions are found to be increasing with the increase in load. It is also observed from the figure that the CO emission of $H_2$ enrichment for all the operating parameters is lower than that of diesel. The CO emission for 0.60 lpm $H_2$ enriched operation is 0.036% by volume compared to 0.047% by volume for neat diesel at 5% load. At full load the $H_2$ enrichment results an increase in CO emission compared to part load operations. The value of CO being 0.634% by volume for 0.60 lpm $H_2$ enrichment compared to that of diesel of 0.980% by volume. For all engine loads, CO emissions for 0.15, 0.30, 0.45, and 0.60 lpm $H_2$ addition decreased by 4.37, 12.61, 17.13, and 23.94% compared to those of pure diesel, respectively. The reduction in CO in $H_2$ enrichment conditions is due to the absence of carbon in $H_2$ fuel.

### *3.3.5. Carbon dioxide ($CO_2$)*

$CO_2$ emission is produced by complete combustion of fuel. Ideally, combustion of a HC should produce only $CO_2$ and water ($H_2O$) [36]. The variation of $CO_2$ with the engine load for different $H_2$ addition into inlet air is depicted in Fig. 6b. As expected, the $CO_2$ emission increases with the increasing load. The main reason of increasing of $CO_2$ with increasing load is more fuel injected into the engine. The other reasons are increasing in combustion temperature and oxidization rates.

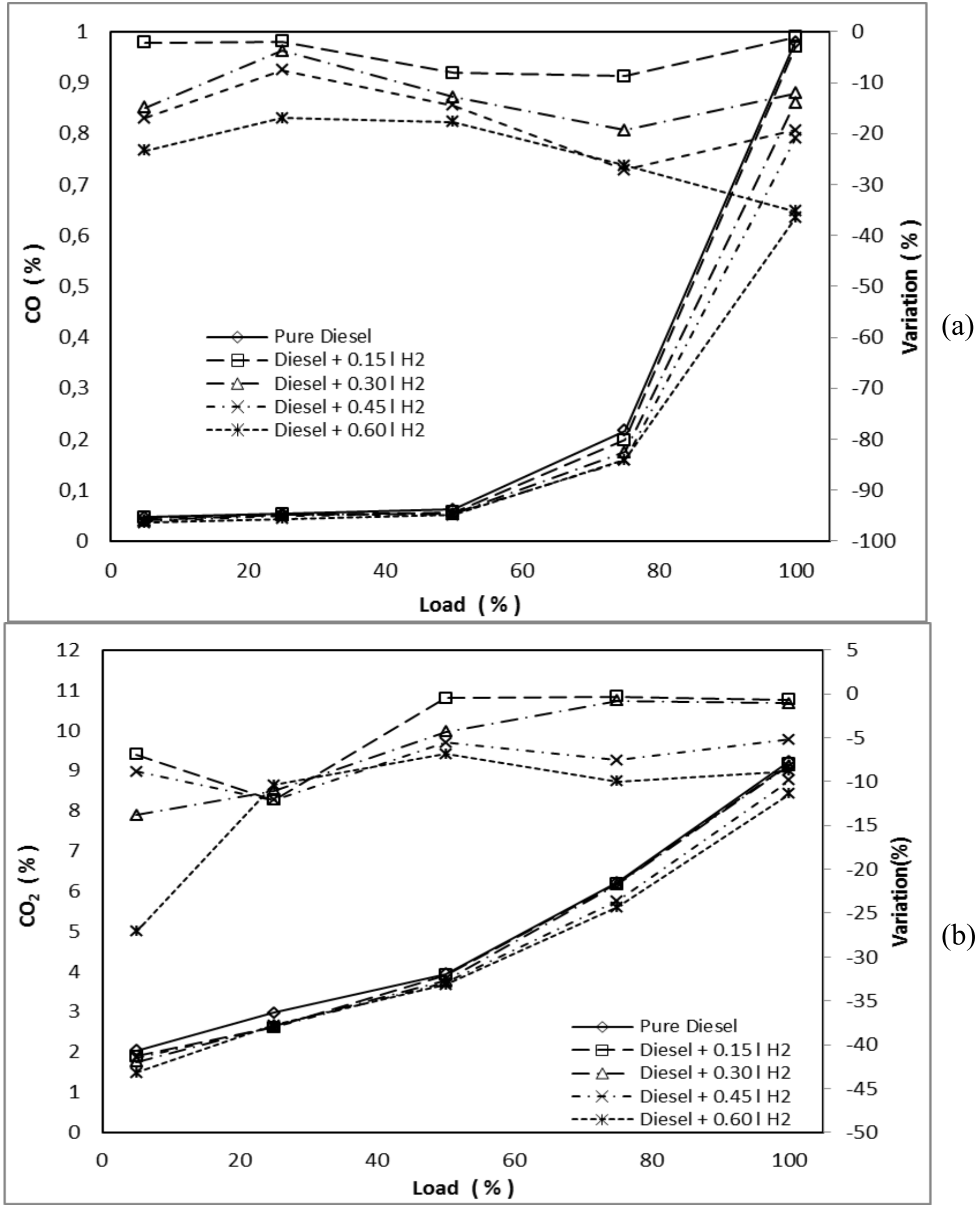

**Figure 6.** Variation of CO (a) and $CO_2$ (b) emissions

As seen in Fig. 6b, the $CO_2$ values are lesser for $H_2$ enriched conditions compared to neat diesel condition. The $CO_2$ for 0.60 lpm $H_2$ enrichment is 5.60% by volume compared to 6.22% by volume for pure diesel at 75% load. At full load, the $CO_2$ for 0.60 lpm $H_2$ enrichment is 8.42% by volume compared to 9.23% by volume for diesel. For all engine loads, $CO_2$ emissions decreased by 4.09, 6.21, 7.85, and 12.62% for 0.15, 0.30, 0.45, and 0.60 lpm $H_2$ addition compared to those of neat diesel, respectively. The reasons of reduction in $CO_2$ concentration with $H_2$ addition into the inlet mixture are burning of $H_2$ supplies energy without bringing carbon into the engine and the improved thermal efficiency benefiting from the improved combustion [37].

## 4. Conclusions

In this study, the effects of addition $H_2$ into the intake air of CI engine on the performance and emissions characteristics of single cylinder, air cooled, DI-CI engine were experimentally investigated. An electrolysis unit was built to produce $H_2$, which was then fed into the intake manifold of the CI engine. The CI engine was tested with addition different amount of $H_2$ into the intake air (0.15, 0.30, 0.45, and 0.60 lpm) at different engine load (5%, 25%, 50%, 75%, and full load) and the constant speed, 2200 rpm. From the experimental results, the following conclusions were made:

1) Addition of $H_2$ into the intake air has a significant effect on the engine performance and emissions because $H_2$ has excellent effects on the fuel spray combustion.
2) Increasing amount of $H_2$ into the inlet air resulted to decrease in BSFC and BSEC while resulted to increase BTE at all load conditions. This is probably the result of uniformity in mixture formation and higher flame speed of $H_2$ leads to better combustion. The best results in terms of BSFC, BSEC and BTE were obtained at 0.60 lpm addition of $H_2$.
3) $NO_x$ emissions generally decreased for all $H_2$ enrichment conditions. However, combustion temperature only increased for 0.6 lpm $H_2$ addition into the inlet air at higher loads. This caused to higher quantity of $NO_x$ formation.
4) The better uniformity in mixture formation with $H_2$ enrichment and higher flame speed of $H_2$ leads to better combustion resulting in an improvement in SD, HC and CO emissions. The optimum emissions were found to be at 0.60 lpm $H_2$ enrichment.
5) $H_2$ leads to more complete combustion. $CO_2$ concentration are lesser for $H_2$ enriched conditions compared to neat diesel condition due to burning of $H_2$ supplies energy without bringing carbon into the engine and the improved thermal efficiency benefiting from the better combustion.

Consequently addition of small amount of $H_2$ produced by electrolysis into the inlet air of DI-CI engine results in improved performance level and generally lowered emission level compared to the case of neat diesel operation.

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