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

by

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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*

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 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 NO_x 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 NO_x increased with increasing H_2-to-C ratio. Lee *et al.* [12] studied on H_2 mixed with the intake air by using injector 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 NO_x emissions were obtained when start of injection was advanced. As a result of less carbon content in the fuel, it was also observed that HC and 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. The NO_x emissions reduced one-fifth of the conventional case up to 90% H_2 enrichment at medium engine load. Conversely at full load, NO_x 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 NO_x compared with diesel.

However higher NO_x emissions that has an undesirable effect on environment is an obvious drawback of H_2-operated engines. The NO_x 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 NO_x 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 NO_x formation [23, 24]. Using of H_2 in dual fuel mode with exhaust gas recirculation (EGR) technique also resulted in lower NO_x 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 [26-28]. 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 NO_x 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 NO_x 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 Lpm) into the intake air at different engine load (5%, 25%, 50%, 75%, and full load) and the constant speed, 2200 rpm.

Experimental set-up

The Diesel engine used for the study was a DI, single cylinder; 4-stroke, air-cooled Lombardini 6 LD 400 engine. Bore and stroke of the engine are 86 mm and 68 mm, respectively. The compression ratio is 18:1. Maximum engine power and torque are 8 kW and 21 Nm, 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 ±2 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 type-K thermocouples. Accuracy of the thermocouples is ±1 °C. The H_2 was generated by electrolyzing water using an O-H_2 generator machine.

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 H_2 gas was determined. The generated H_2 is then passed through a flow meter before it is introduced to the engine by the use of the air inlet manifold. The H_2 was passed through a non-return valve, preventing reverse flow of H_2 into the system. A flame arrestor was installed into the H_2 line in order to prevent flash-back into the H_2-containing system. The H_2 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 H_2 into the engine. Then, with no change in the experimental conditions, a small amount of H_2 (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 H_2 is called as enrichment air with H_2. 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 CO_2, CO, HC, and NO_x were measured using an BOSCH-750 exhaust gas analyzer and SD was mea-

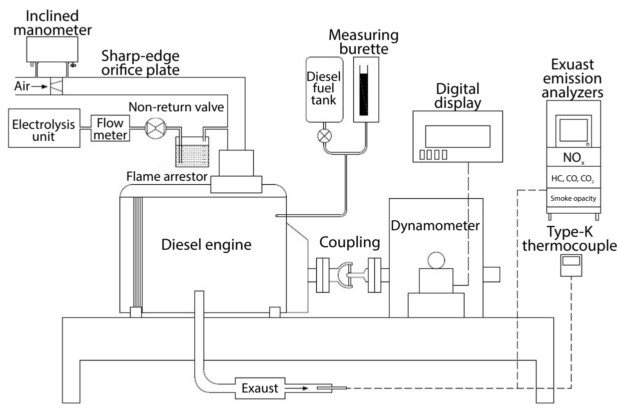

Figure 1. Schematic diagram of experimental set-up

sured using a smoke analyzer. Accuracy of CO_2, CO, HC, and NO_x 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 set- -up is plotted in fig. 1.

Results and discussion

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).

Brake thermal efficiency

The BTE is defined as the ratio of the brake power to fuel consumption and lower heat value (LHV). The 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 BTE. 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.

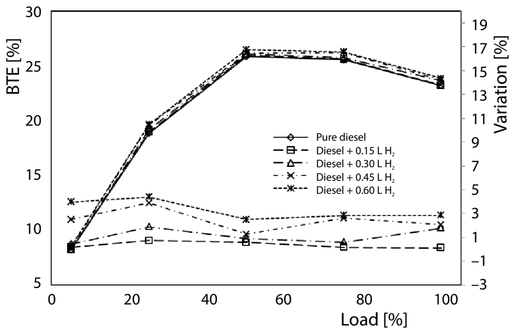

Figure 2. Variation of BTE

Brake specific fuel consumption

The 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. 3(a). 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. 3(a), 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.

Brake specific energy consumption

The BSEC is described as multiplication of BSFC and LHV [34]. As shown in the fig. 3(b), the BSEC reduces with increasing engine loads because of noticeably diminishing BSFC for the all fuel mixtures. It is also observed from the fig. 3(b) 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.

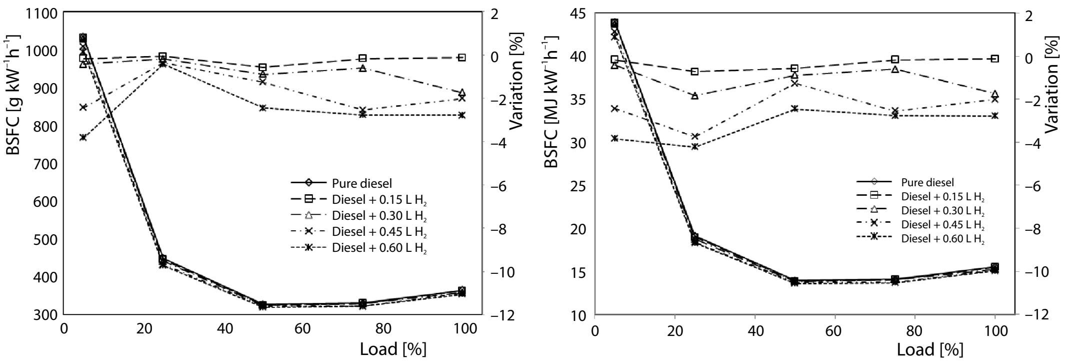

Figure 3. Variation of BSFC (a), and BSEC (b)

Exhaust gas temperature

Figure 4(a) 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.

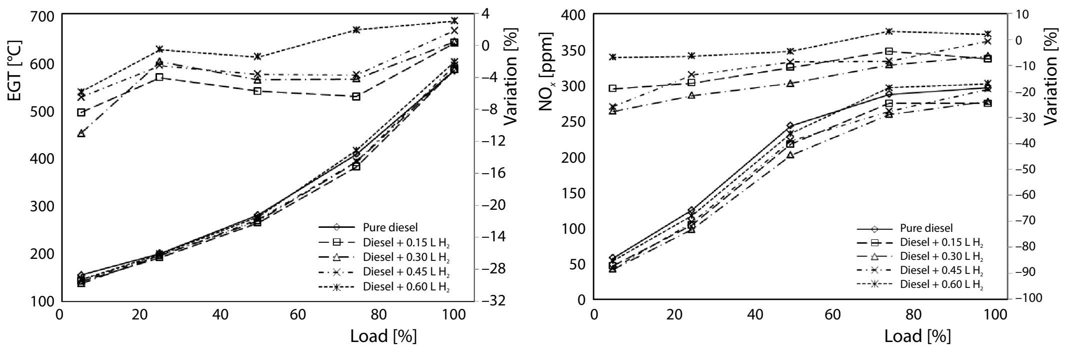

Figure 4. Variation of EGT (a), and NO$_x$ emissions (b)

Exhaust emissions

Nitrogen oxides

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. The NO_x is collective term used to refer to NO and NO_2. The 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. 4(b).

The NO_x emissions increased with the increasing engine load because of increasing combustion temperature as shown in fig. 4(b). The 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% 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.

Smoke density

Due to the heterogeneous nature of diesel combustion, there is a wide distribution of air/fuel ratios within the cylinder. The SD is attributed to either air/fuel mixtures that are too lean to autoignite or to support a propagating flame, or air/fuel 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. 5(a). 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. 5(a), 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. The 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.

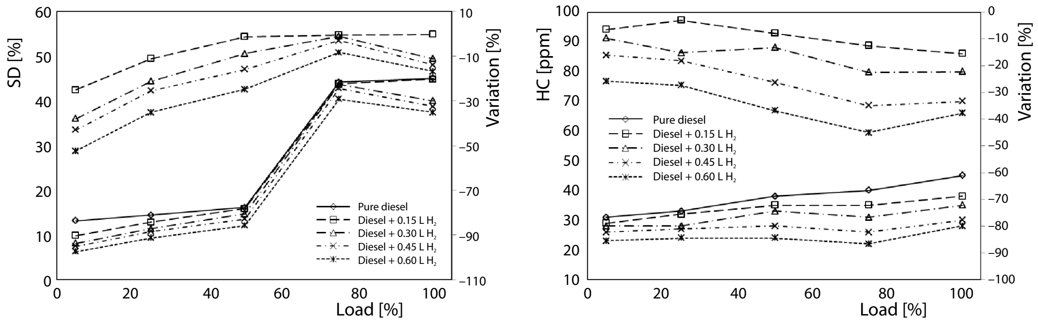

Figure 5. Variation of SD (a), and HC (b)

Hydrocarbon

The variation of HC with engine load for different percent H_2 into the inlet mixture is given in fig. 5(b). 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.

Carbon monoxide

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].

The variation of CO with engine load for the different amount of H_2 into the inlet air is presented in fig. 6(a). 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.

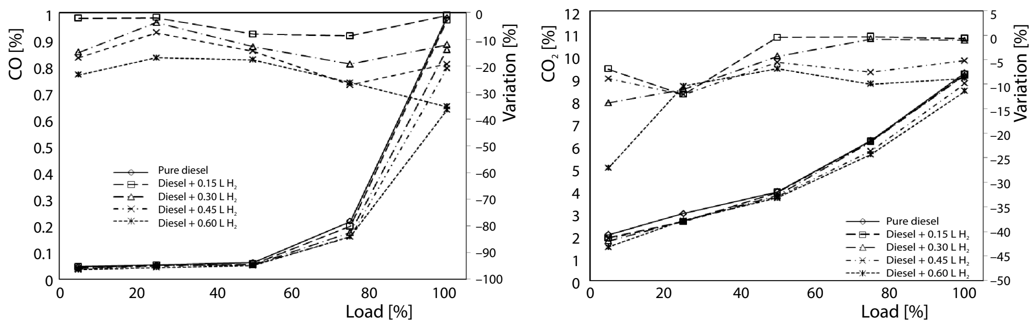

Figure 6. Variation of CO (a) and CO_2 (b) emissions

Carbon dioxide

The 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. 6(b). 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.

As seen in fig. 6(b), 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].

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.

- 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.
- 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.
- The 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.
- 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.
- The H_2 leads to more complete combustion. The 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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