An Experimental Investigation on Performance and Emissions of a Multi Cylinder Diesel Engine Fueled with Hydrogen-Diesel Blends

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Abstract: Diesel engines are major contributors of air pollution by its exhaust gasses such as particular matter, carbon oxides, oxides of nitrogen, and sulfur compounds. Also, the diesel as a fossil fuel is threatened to decay with depletion of its sources. Hydrogen as a renewal energy and promising fuel might use to solve that troubles and crisis. A multi cylinder, natural aspiration, four stroke, compression ignition, and water cooled engine is tested under hydrogen diesel different blends and at different operating conditions. A hydrogen induction set up is built in the lab with all of the acquitting sensors and measuring instruments. The safety rules are considered. A continuous hydrogen induction in the inlet manifold is selected technique for this investigation. Experimental tests are done to investigate engine thermal performance and exhaust emission constituents under those blends circumstances. The optimum operating conditions and optimum parameters for those blends are found. The investigation led to find that, the optimum rate of hydrogen induction is 7.5 lpm. This optimum rate reduced the diesel fuel consumption by 20 % and increased the brake thermal efficiency by about 8-9%. The NO_X emission is reduced.

Keywords: *Hydrogen, Compression ignition engine, Performance, Exhaust emission, Dual Fuel.*

1. Introduction

Since 1878 to this day, diesel engine played the role of one primary source of power in human life. Many life sectors are depended on diesel engine such as agriculture and transportation. Diesel engine possesses a high reliability and durability with reasonable fuel consumption. Unfortunately, diesel engine is the main contributor to world's pollution. It has smoke and NO_X as major exhaust emissions. Numerous research efforts are concentrated on finding solutions to this problem. In 1970, the energy crisis ignited the competitions and research to find new energy sources or renewable energies. For both challenges, save our environment and save the energy sources, hydrogen is found as a promising solution. Hydrogen is nearly ideally suited as energy carrier because of its physical and chemical properties. It can be produced from water and conversely, on combustion forms water again in a closed cycle with very low formation of NO_X. It seems that the improvement in the engine performance under steady conditions is mainly attributed to the contribution of the hydrogen properties to the combustion process. The use of hydrogen with diesel engine might supplement wholly or partially without substantial hardware modification in arrangement of diesel engine [1]. The replacement of diesel by hydrogen totally needs high compression ratio above 29 along with a drop in the engine power and efficiency. Duel fuel mode or hydrogen diesel blends are more preferable [2]. The idea of using hot diesel drops as an igniter to air- hydrogen blend is applied. Many techniques have been studied and tested to inject or induct the hydrogen in air manifold or air intake passage. Carburetions, timing intake injection and induction, continuous injection or induction are the techniques mostly used [3].

Each technique has advantage and disadvantage. However, indirect injection or induction techniques pose no requirement of high compression ratio to run the engine under hydrogen-diesel blend. Verhelst at el. [4] used air port injection method to investigate the hydrogen effect on SI engine which might apply in diesel engine as well. Masood et al [5, 6] investigated direct injection and in port induction with modeling to those blends. Saravanan et al. [7-10] investigated different techniques in the hydrogen injection and induction with recycling to exhaust gas and tested the timing and duration of hydrogen injection.

In this paper, a continuous induction of hydrogen in the air inlet manifold of a multi cylinder, compression ignition engine is adopted to investigate engine performance and exhaust gas emission constituents experimentally under different hydrogen induction rates and loads.

2. Experimental set-up

The experimental set up used for the present investigation consists of a four cylinder, four stroke, water cooled, indirect injection, naturally aspirated, and compression ignition engine developing a rated maximum power of 37 hp or 26.7 kW and running at varied speed equipped with a hydrogen induction system and an eddy current dynamometer with variable loading arrangement. The eddy current dynamometer gives the value of load in terms of Amp. only. The engine is coupled directly to the dynamometer and is mounted on a test bed with suitable connections for lubricating and cooling systems. The specification of the engine used for the study is given in Table 1.

Fig. 1 illustrates the schematic of the set up. Hydrogen induction system consists of high pressure hydrogen gas cylinder at 14.6 bar pressure, regulating valves, fine valve and digital mass flow meter to measure hydrogen flow rate. Nitrogen gas cylinder, flame arrestor, flame trap, non-return valve are used as a protection devices. PT 100 thermometer type is used to measure the exhaust temperature. Diesel weight flow rate is measured using strain gauge. Air surge tank with vertical water manometer is used to measure air pressure difference and to calculate the airflow rate in inlet manifold pipe. While a non contact tachometer is used to measure the engine speed. All the instruments are calibrated against traceable standards.

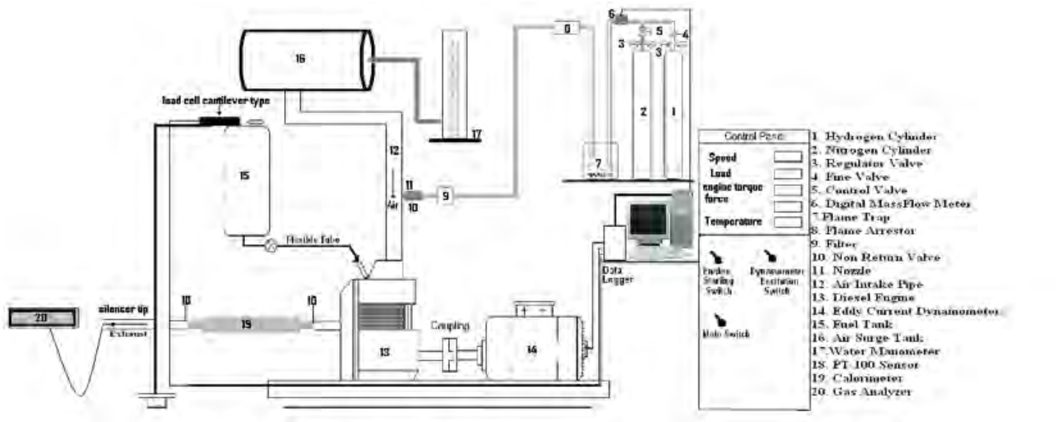

Fig. 1. The experimental setup

Table 1. Engine specification

Make and model	Stride Engine 1.5 E2 DSL
General details	Four cylinder, four stroke, compression ignition, vertical, water cooled, indirect injection
Bore	73 mm
Stroke	88.9 mm
Compression ratio	23:1
Max. power	27.6 kW @ 4000 rpm
Max. torque	83.4 Nm @2250 rpm
Capacity	1489 cm^3

3. Experimental procedure

The following step by step procedure is followed during the experimental investigation:
Start and run the diesel engine at 1500 rpm (most of previous investigations tested the diesel engine at this rate speed) for about 15 minutes to warm the engine and attain steady state condition before the data is acquired.

1. Set the fuel supply system in only diesel mode and record the data of fuel consumption rate, air difference pressure, engine speed, exhaust gas temperature, and exhaust gas constituents under no-load condition.
2. Repeat the observations under different load conditions at the eddy current dynamometer with loadings at 0.5, 1, 1.5, and 2 Amp. of load.
3. Run the engine on diesel mode. Then, set the induction of hydrogen in the an inlet manifold at a specified rate of 1 lpm and run the engine under dual fuel mode to attain steady state condition.
4. Record the data of fuel consumption rate, air pressure difference, engine speed, exhaust gas temperature, and exhaust gas constituents under 0.5 Amp. load condition.
5. Repeat the procedure in steps 4 and 5 under different load conditions at the dynamometer with loadings at 1, 1.5 and 2 Amp.
6. Repeat the experiment for different hydrogen induction rates of 2, 3,…, up to 18 lpm.
7. Close the hydrogen cylinder valve and open the nitrogen cylinder valve and purge the hydrogen gas from the induction system to avoid any burning of residual hydrogen gas.
8. Stop the induction of nitrogen and bring the engine to no load condition before switching off the engine.

4. Results and discussion

From an initial experimental study, it is found that the maximum rate of hydrogen induction at a given loading is to be restricted up to 18 lpm and the maximum loading possible on the engine is 2 Amp. due to engine load capacity restriction. This is the constraint within which the present experimental investigation is carried out.

Fig. 2 illustrates the relation between brake thermal efficiency and hydrogen induction rate at 1500 rpm speed and various loads. The brake thermal efficiency calculated by [1]:

$$brake\ thermal\ efficiency\ (\%) = \frac{Brake\ Power}{(m_f \times CV_D + m_{H2} \times CV_{H2})} \quad (1)$$

It is seen that, the brake thermal efficiency significantly increases with hydrogen induction rate. The rate of increase in brake thermal efficiency with continuous hydrogen induction is found to be higher at higher loads of 1, 1.5, and 2 Amp. load, while, there is no significant change in the efficiency with load of 0.5 Amp. The reason may be attributed to the higher caloric value of hydrogen which is approximately twice that of diesel. For a given load and speed condition, the influence of extra energy addition due to hydrogen induction on brake thermal efficiency is apparent from Eq. (1). The extra energy induction decreases the need of diesel fuel required. At full load, there is 20% increasing in brake thermal efficiency when the hydrogen induction rate changed between 0 lpm and 18 lpm.

Fig. 3 gives the variation in diesel fuel consumption with hydrogen induction rate for various loading (0, 0.5, 1, 1.5, and 2 Amp.) of diesel engine running at 1500 rpm. The engine running at constant speed needs less amount of diesel at a specified brake load due to extra energy available from hydrogen. It can also be noticed that the rate of reduction in diesel fuel consumption is higher at higher loading. At high load condition, the rate of reduction in diesel fuel consumption is found to be about 40% between hydrogen induction rate from 0 to 18 lpm. This is observed to be true for higher loading of 1, 1.5, and 2 Amp. However, at no loading or light loadings of 0 and 0.5 Amp respectively, the reduction in diesel fuel consumption for hydrogen induction rate from 0 to 18 lpm is found to be about 25-30 %.

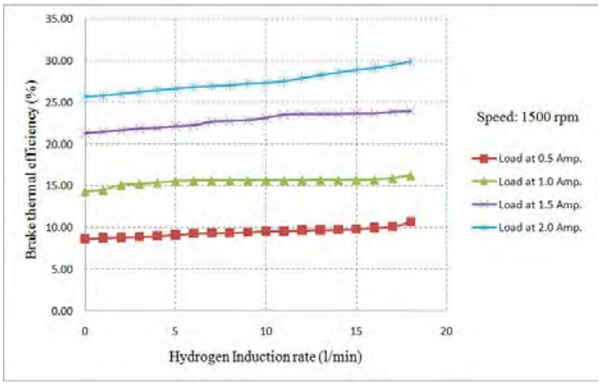

Fig. 2 Variation of brake thermal efficiency with hydrogen induction rate for various loading of diesel engine

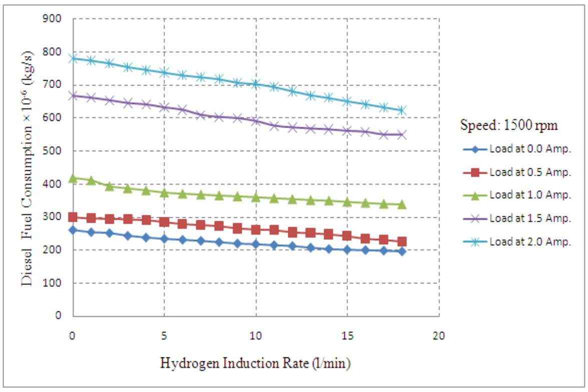

Fig.3 Variation of diesel fuel consumption with hydrogen induction rate for various loading of diesel engine

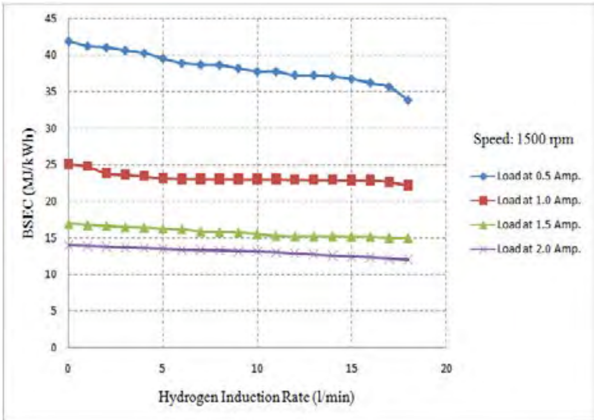

Fig. 4 Variation of brake thermal efficiencywith hydrogen induction rate for variousloading of diesel engine

The variation of the brake specific energy consumption (BSEC) with hydrogen induction rate at different loading conditions is shown in Fig. 4. It is seen that the hydrogen induction in the atmospheric air intake manifold of the engine enhances the consumption of energy to produce more usable power. Basically, the BSEC decreases with increase in load with the engine running at a given constant speed. The same trend is observed with various hydrogen induction rate also. With the induction of hydrogen, the decrease in BSEC is more significant when the load applied is beyond 1.0 Amp.

At constant induction rate, the decrease in BSEC is of the order of about 3 times when the load is increased from 0.5 Amp. to 2.0 Amp.

Fig. 5 illustrates the effect of hydrogen induction rate on the exhaust temperature of diesel engine at different loading conditions with speed held at 1500 rpm. The increase in exhaust temperature is an indicator of combustion process behavior. The increment in exhaust temperature is directly indicating to the increment in the energy released increment in the combustion chamber. It can be noticed a margin increase in exhaust temperature due to the high caloric value of hydrogen.

The effect of hydrogen induction rate on volumetric efficiency is represented in Fig. 6. It is observed that irrespective of the loading condition, volumetric efficiency decreases by about 10% when the hydrogen induction rate increased from 0 to 18 lpm. The reason for such a trend may be attributed to the following. A naturally aspirated diesel engine working at a constant speed is found to operate with constant air suction rate. The rate of suction air decreases with increase of load resulting in a decrease of volumetric efficiency. In the range of loading under consideration, the decrease is found to be a maximum of about 5%. However, at a constant speed and load, the volume intake of air decreases when hydrogen induction rate is increased which results in decrease of volumetric efficiency. The reduction in suction air rate leads to incomplete combustion affecting obviously the emission characteristics.

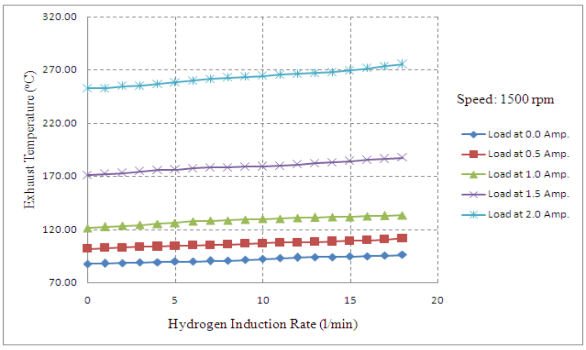

Fig. 5 Variation of exhaust temperature with hydrogen induction rate for various loading of diesel engine

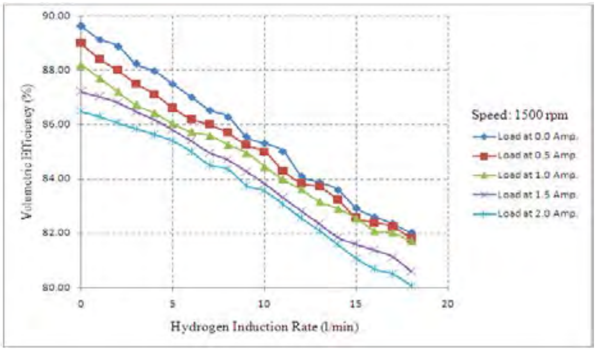

Fig. 6 Variation of volumetric efficiency with hydrogen induction rate for various loading of diesel engine

Fig. 7 shows the variation of equivalence ratio with continuous hydrogen induction rate for various loading of diesel engine running at constant speed. The trend is in consistent with that observed in Fig. 3. For diesel hydrogen duel fuel system, the equivalence ratio is calculated using Eq. (2) [12]. The equivalence ratio increases with loading increase. The equivalence ratio decreased as hydrogen induction rate increased for a given load.

$$\emptyset = \frac{\frac{[G]}{[Air] - \frac{[H_2]}{\left(\frac{[H_2]}{[Air]}\right)_{st}}}}{\left(\frac{[G]}{[Air]}\right)_{st}} \qquad (2)$$

Where, ϕ is equivalence ratio, [G], [Air], and $[H_2]$ are respectively diesel, air, and hydrogen molar concentrations. Subscript ‘st’ stands for stoichiometric. The thermal performance evaluation of the effect of continuous hydrogen induction in inlet manifold to naturally aspirated multi cylinder water cooled diesel engine running at a constant speed of 1500 rpm indicates improvement in brake thermal efficiency. The notable feature of the effect of the hydrogen induction is the significant reduction in diesel consumption rate required. However, an optimum hydrogen induction rate could not be ascertained for maximizing thermal efficiency and minimizing diesel consumption rate as hydrogen induction rate beyond 18 lpm poses serious flash back problems.

In view of the above observations, experimental investigations are further carried out to quantitatively estimate the emission characteristics and evaluate whether there should be an optimum hydrogen induction rate, which does not seriously affect pollutant emission rates. Figs. 8-12 represent the effect of continuous hydrogen induction rate on the emission of the various exhaust constituent gases such as CO, CO_2, HC, NO_X, and O_2 when the engine is run at different load.

It is seen from Fig. 8 that, the hydrogen induction rate has significant effect on CO emission. The reason for such a trend is due to the proportionate decrease in the content of inlet manifold air. In the case of fuel rich mixture, the CO emission increases while for that of lean fuel mixture, it remains fairly constant. As diesel engines are operated with lean fuel mixture, CO emission is generally low [13]. However, with hydrogen induction rate increased from no induction to 18 lpm, the CO percentage emissions increases from about 0.15% to 0.95% with the loading of 2 Amp. Similarly, it is found that there is significant effect of hydrogen induction rate on CO emission for the engine running at 0, 0.5, 1 and 1.5 Amp. loads.

Since diesel consumption rate increases with increase in loading. There is an increase in CO_2 emission by about three times (i.e from about 2.5% to 7.5%) with no hydrogen induction. Further, similar trends are observed with hydrogen induction rate, Fig. 9. Further, it is seen that there is no significant effect on CO_2 emission when hydrogen induction rate increased from 0 to 18 lpm for engine running at constant speed and load.

Fig. 10 illustrates the effect of hydrogen induction rate on unburned hydrocarbon (HC) emission. It is observed that there is a considerable increase in HC emission when hydrogen induction rate is increased beyond 7.5 lpm. At 18 lpm hydrogen induction rate the HC decreased by about 8 times when the load varied between 0 and 2 Amp.

Hydrocarbons, or more appropiately organic emissions, are the consequence of incomplete combustion of the hydrocarbon fuel. The level of HC in the exhaust gases is generally specified in terms of total hydrocarbon concentration expressed in parts per million carbon atome or volume percentage (as in present work). While total hydrocarbon emission is a useful measure of combustion inefficiency, it is not necessarily a significant index of pollutant emissions. Engine exhaust gases contain a wide variety of hydrocarbon compounds. Hydrocarbon compounds are divided into different categories and scales. The simplest scale, which divides the HC into classes as methane and non methane hydrocarbons, probably best approximates the end result for all HC emissions. All hydrocarbons except methane react, given enough time. In diesel the HC constituents vary from methane to the heaviest hydrocarbons. The multi gas analyzer used into present work measured the HC on basis of the methane. Unburned hydrocarbons or partially oxidized hydrocarbons emission levels from diesel vary widely with operating conditions, and different HC formation mechanisms are likely to be most important at different operating modes. Engine idling or low speed and light load operations produce significantly high hydrocarbon emissions than full load or high speed operation [11]. These notes can be observed in the Fig. 10. The increment in hydrogen induction rate causes reduction in the intake air which results in a displacement of some volume of the intake air. With increase in load , therefore, the percent content of CO in exhaust gases slightly decreases for a given hydrogen induction rate. This slight reduction in per cent content of CO in exhaust gases may be either due to the formation of lean mixture when only diesel is used as base fuel or/and due to the conversion of CO to CO2.

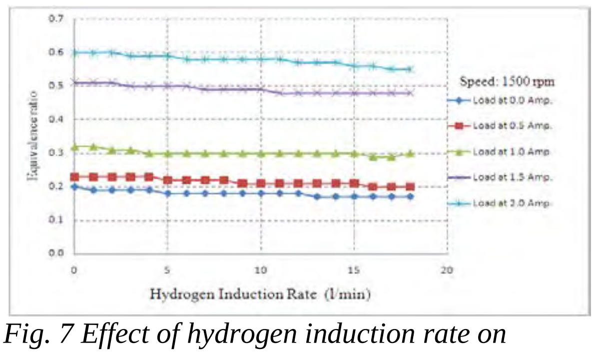

Fig. 7 Effect of hydrogen induction rate on equivalence ratio

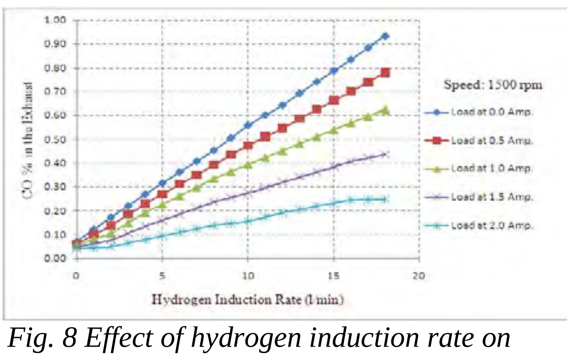

Fig. 8 Effect of hydrogen induction rate on on CO emission at difference loading

The effect of hydrogen induction rate on NO_X emission is given in Fig. 11. It is seen that there is 20% decrease in NO_X emission at smaller loading of 0, 0.5, and 1 Amp. from the condition of no induction to 7.5 lpm hydrogen induction rate. However, at higher loading, the decrease in NO_X emission is only about 6-7% between the same ranges of hydrogen induction rate. The constituent gases of NO_X emission are mainly NO and NO_2. Although the amount of the NO_2 is increased with higher hydrogen induction rate, the decrease in the amount of constituent gas NO plays a dominant role in the decrement in NO_X formation. The reduction in the amount of intake air has contributed to the reduction in NO_X emission in spite of the increase in the exhaust temperature. Fig. 12 illustrates the effect of hydrogen induction rate on O_2 emission. It is observed that there is only a marginal decrease in O_2 emission with increase in hydrogen induction rate. However, as the load on the engine is increased from 0 to 2 Amp., there is a 30 – 35 % decrease in O_2 emission.

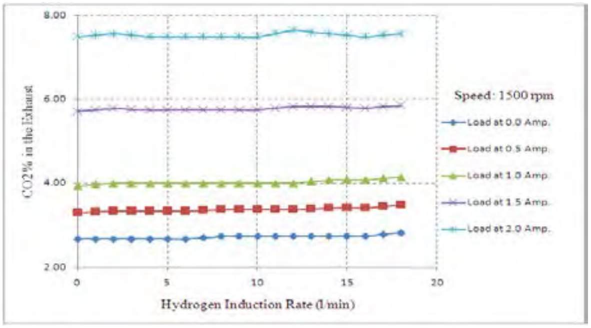

Fig. 9 Effect of hydrogen induction rate on CO_2 emision at difference loading

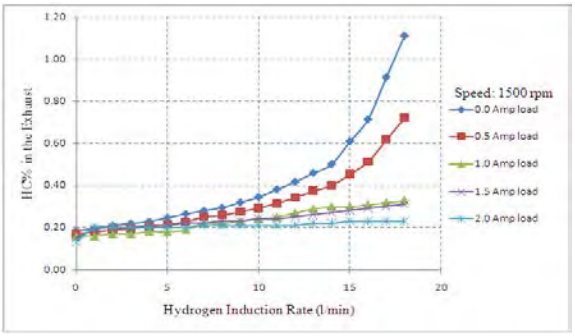

Fig. 10 Effect of hydrogen induction rate on HC emission at difference loading

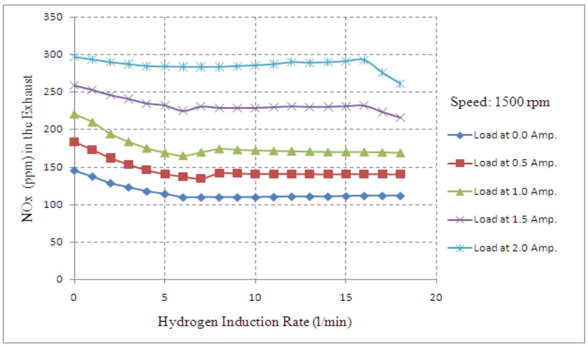

Fig. 11 Effect of hydrogen induction rate on NO_X at difference loading

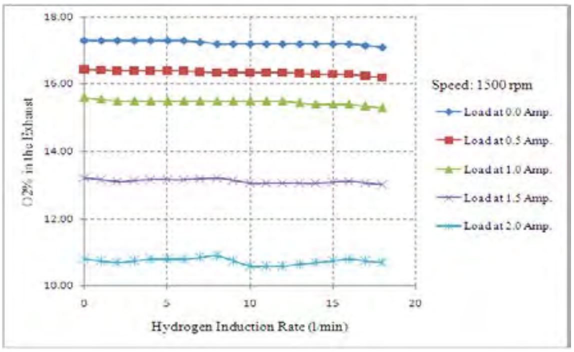

Fig. 12 Effect of hydrogen induction rate on O_2 emission at difference loading

5. Conclusion

Based on the experimental studies conducted on the thermal performance and pollutant emissions using a indirect injection multi cylinder naturally aspirated diesel engine with and without continuous hydrogen induction in the inlet manifold, the following conclusions are drawn:

1. A continuous hydrogen induction into the inlet manifold is a unique way of addressing simultaneously issues related to thermal performance and pollutant emission from diesel engine operated with diesel as a fuel. The system may be treated as hydrogen diesel dual fuel system as energy from hydrogen is also utilized.
2. There is a monotonous effect of continuous hydrogen induction rate on thermal performance parameters such as brake thermal efficiency, diesel fuel consumption rate and volumetric efficiency. And hence thermal performance tests alone cannot predict optimum hydrogen induction rate needed.

3. Based on both thermal performance and pollutants emission studies, it is seen that hydrogen induction rate about 7.5 lpm gives an optimum performance keeping the emissions level at a reasonable low levels. At 7.5 lpm, the levels of CO, CO_2 and HC are not increase significantly while the NO_X is reduced. The 7.5 lpm hydrogen induction rate approximately reduced the diesel fuel consumption by 20% and increased the brake thermal efficiency by about 8~9%.

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