Experimental Investigation of the Effect of Hydrogen Manifold Injection on the Performance of Compression Ignition Engines

Haroun A.K. Shahad, Nabeel Abdul-Hadi

Abstract—Experiments were carried out to evaluate the influence of the addition of hydrogen to the inlet air on the performance of a single cylinder direct injection diesel engine. Hydrogen was injected in the inlet manifold. The addition of hydrogen was done on energy replacement basis. It was found that the addition of hydrogen improves the combustion process due to superior combustion characteristics of hydrogen in comparison to conventional diesel fuels. It was also found that 10% energy replacement improves the engine thermal efficiency by about 40% and reduces the sfc by about 35% however the volumetric efficiency was reduced by about 35%.

Keywords—Hydrogen, Blended fuel, Manifold injection , Performance , Combustion

I. INTRODUCTION

INTERNAL combustion engines have been in use for more than a century and have undergone tremendous changes in their design, materials used and operating characteristics. Diesel engine is the most efficient type of internal combustion engines. In past few decades research efforts have been focused largely on better engine design from the perspective of reducing pollutants emission without sacrificing performance and fuel economy. Many researches have been directed towards the development of alternative fuels to achieve this goal. Among the various probable alternative fuels, hydrogen is found to be the most promising due to its clean burning and better combustion properties [1]-[4]. However the high self ignition temperature of hydrogen limits its use in compression ignition engines since the cylinder temperature rise due to compression alone is not enough to initiate combustion, hence an ignition source is required [5]. Hydrogen can be used as a fuel in internal combustion engines either pure or blended with other hydrocarbon fuels. Hydrogen has superior characteristics than hydrocarbon fuels such as wider flammability limits, low ignition energy and higher flame speed [6]. Saravanan, N. and Nagarajan, G [5] studied experimentally the effect of manifold injection of hydrogen on the performance of a hydrogen-diesel dual fuel engine. They found that with manifold injection the engine operates smoothly with a significant improvement in performance and reduction in emissions.

Mohamed Fadhil Al-Dawoodi, [6] studied theoretically the effect of hydrogen blending on the emissions of a medium speed four stroke diesel engine using a quazi-dimensional multi-zone model. They found that hydrogen blending increases maximum cylinder pressure, zonal temperature and rate of heat release. This is due to the reduction in the time required for mixture burring as the presence of hydrogen increases the flame speed.

Li Jing-Ding , Lu Ying-Qing and Du Ting-Shen, [7] performed an experimental study on burning hydrogen-diesel oil mixture. They found that increasing compression ratio is an effective method to improve the combustion characteristics of hydrogen fueled engine. They also found that smoke can be reduced by using hydrogen diesel oil mixture and under low speed high load conditions the results will be better.

Bari, S. and Mohammad Esmail, M. [8] carried out an experimental research to evaluate the performance enhancement of a conventional diesel engine through the addition of H_2/O_2 mixture generated through water electrolysis. The tests were done at constant speed with varying load and amount of H_2/O_2 mixture. The results showed that the engine brake thermal efficiency was improved with fuel saving. The emissions of HC, CO_2 and CO was decreased while the NO_x emissions was increased.

Tomita Eiji, et.al [9] carried out an experimental study by inducing hydrogen from the intake manifold into the cylinder of a diesel engine and injecting light oil directly inside the cylinder. They found that hydrogen induction reduced smoke, CO, CO_2 and NO_x while the brake thermal efficiency was slightly reduced.

Saravanan, N. and Nagarajan, G. [10] studied experimentally hydrogen as an air enrichment medium with diesel as an ignition source in a stationary diesel engine system to improve engine performance and reduce emissions. The results showed less smoke levels and less particulates emission. The results also showed higher brake thermal efficiency and hence lower specific energy consumption.

In the present study the effect of manifold hydrogen injection on the performance of a small high speed diesel engine was studied. Hydrogen was used as a blending fuel. The blending was done on energy replacement basis.

II. EXPERIMENTAL SETUP AND PROCEDURE

The tests program was carried out on a lumberdini single cylinder four stroke high speed diesel engine with a compression ratio of 18. The engine bore and stroke are 78 mm and 68 mm respectively. The engine was loaded via a DC dynamometer type SUD10 [11]. The diesel fuel consumption was calculated by measuring the time required to consume a fixed volume of fuel and using the following equation.

$$\dot{m}_d = \frac{V \times \rho_d}{t} \qquad (1)$$

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The air volume flow rate was calculated using the following equation,

$$\dot{V}_a = C_d \times A \times \sqrt{\frac{2\Delta P}{\rho_a}} \quad (2)$$

The pressure drop $\boldsymbol{\Delta P}$ was measured by a differential manometer.

The engine speed was measured by means of a magnetic transducer and a voltage frequency converter type IFR12-24-11 [11].

The inlet manifold of the engine was modified to allow for hydrogen injection . The hydrogen injector was mounted on the inlet manifold at 10 cm upstream of the inlet valve at an angle of 45° to allow good mixing of hydrogen and air. These specifications are obtained from reference [12].

The timing and duration of hydrogen injection process is controlled by a specially designed and manufactured control unit which takes its input signal from an optical encoder mounted on the engine crank shaft [1]. The hydrogen gas is supplied from a hydrogen bottle which is at a pressure of 86 bar. Two pressure reduction valves were used to reduce the hydrogen pressure to 2 bar where it is injected into the manifold. The hydrogen volume flow rate was measured using a hydrogen flow meter. The tests were done at constant speed and variable load. Three different speeds were chosen namely; 1000, 1250 and 1500 rpm. For each speed the load was varied from no load conditions to 80%. The test rig is shown in fig 1.

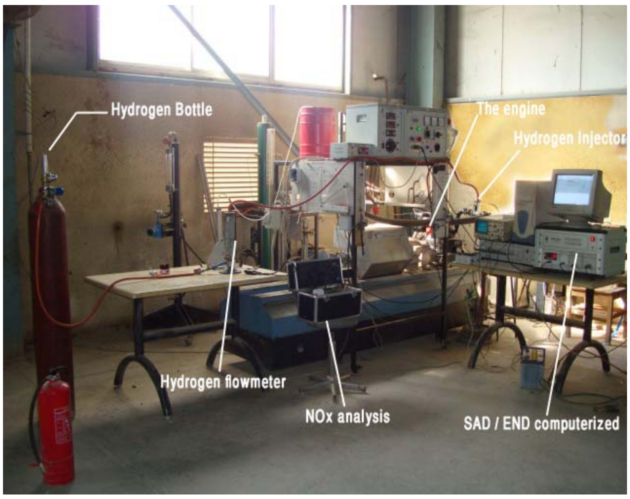

Fig. 1 The test rig

The engine power was calculated using the following equation;

$$P = \frac{I \times V}{1000} \quad (3)$$

The engine thermal efficiency was calculated as follows;

$$\eta_{th} = \frac{P}{\dot{Q}} \times 100 \quad (4)$$

$$\dot{Q} = \dot{m}_d \times (LCV)_d + \dot{m}_{H_2} \times (LCV)_{H_2} \quad (5)$$

$$\dot{m}_{H_2} = \rho_{H_2} \times \dot{V}_{H_2} \quad (6)$$

The hydrogen density was calculated at a pressure of 2 bar and 20 °C.

The specific fuel consumption was calculated as;

$$sfc = \frac{(\dot{m}_d + \dot{m}_{H_2}) \times 3600}{P} \quad (7)$$

The volumetric efficiency of the engine was calculated as;

$$\eta_V = \frac{(\dot{V}_{air} + \dot{V}_{H_2})}{\dot{V}_{dis}} \times 100 \quad (8)$$

$$\dot{V}_{dis} = V_{swept} \times \frac{rps}{2} \quad (9)$$

$$bmep = \frac{P}{\dot{V}_{dis}} \quad (10)$$

III. RESULTS AND DISCUSSION

Fig. 2,3,4 and 5 show the variation of thermal efficiency , volumetric efficiency , specific fuel consumption and mean effective pressure respectively with load for different hydrogen blending ratios . The result are at 1000 rpm .

The thermal efficiency increases as the percentage of hydrogen blending increases for constant speed and load. This due to the improvement of combustion process caused by the presence of hydrogen since the presence of hydrogen improves mixing process of fuel mixture with air . Also the presence of hydrogen reduces the duration of combustion process. The thermal efficiency reaches its maximum valve at about 80% load for all hydrogen blending ratios. At higher loads the efficiency drops due to incomplete combustion of richer mixture.

The volumetric efficiency decreases with load as the percentage of hydrogen blending increases for constant speed. This is due to the effect of hydrogen which reduces air flow through the inlet manifold.

The specific fuel consumption decreases with load as the percentage of hydrogen blending increases for constant speed. This is due to better mixing of fuel mixture with air caused by hydrogen which results in more efficient burning process of fuel mixture. This increases engine power.

The brake mean effective pressure increases with load as the percentage of hydrogen blending increases for constant speed. The reason behind that is the reduction of time of combustion process due to better mixing process of fuel mixture and air.

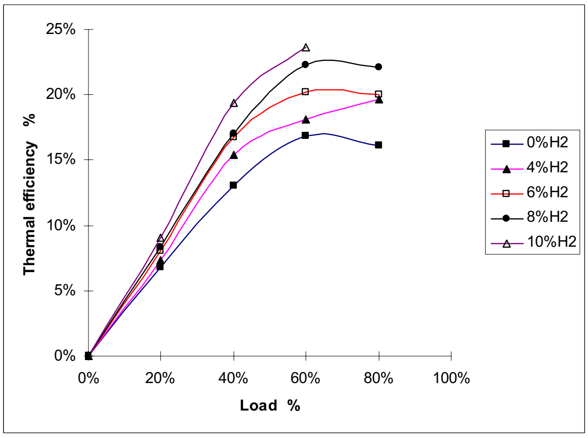

Fig. 2 Effect of load on thermal efficiency for different hydrogen blending ratios at 1000 rpm

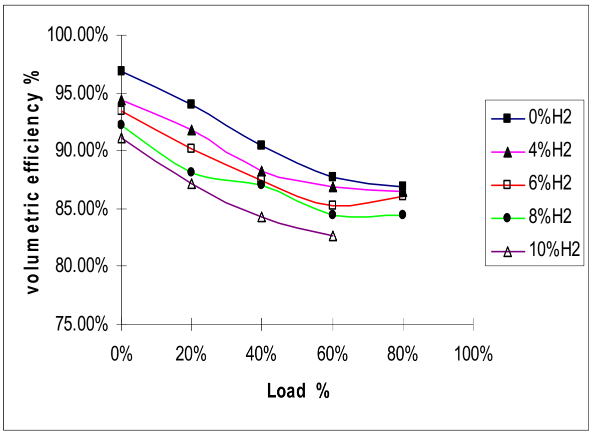

Fig. 3 Effect of load on the volumetric efficiency for different hydrogen blending ratios at 1000 rpm

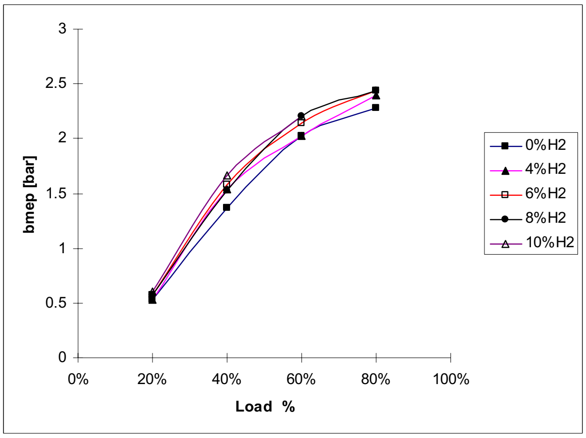

Fig. 4 Effect of load on bmep for different hydrogen blending ratios at 1000 rpm

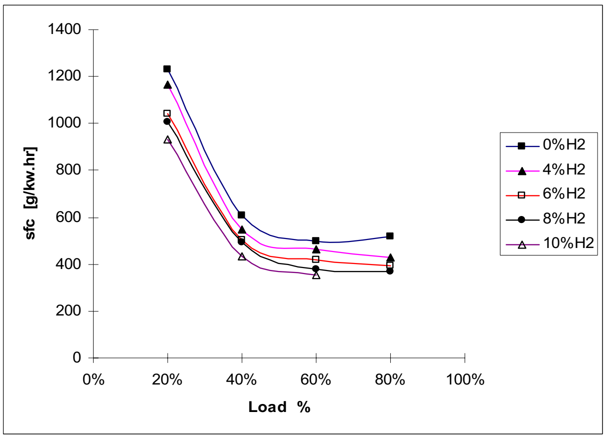

Fig. 5 Effect of load on sfc. for different hydrogen blending ratios at 1000 rpm

Figs. 6, 7, 8 and 9 show the effect of the load at different hydrogen blending ratios on the thermal efficiency ,volumetric efficiency, brake mean effective pressure and specific fuel consumption, respectively . The results are at a constant engine speed of 1250 rpm . These figs show same trends of tested variables as in the case of 1000 rpm but with different values.

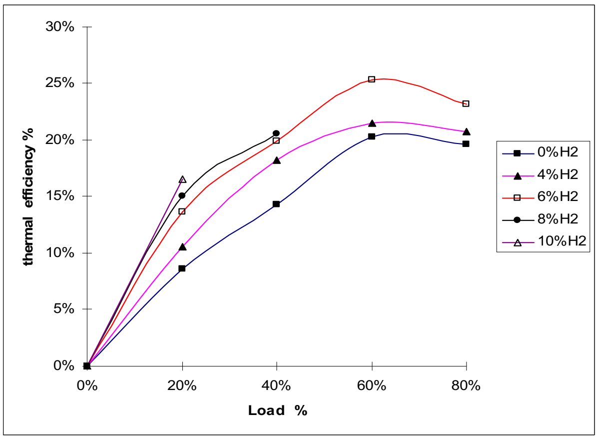

Fig. 6 Effect of load on the thermal efficiency for different hydrogen blending ratios at 1250 rpm

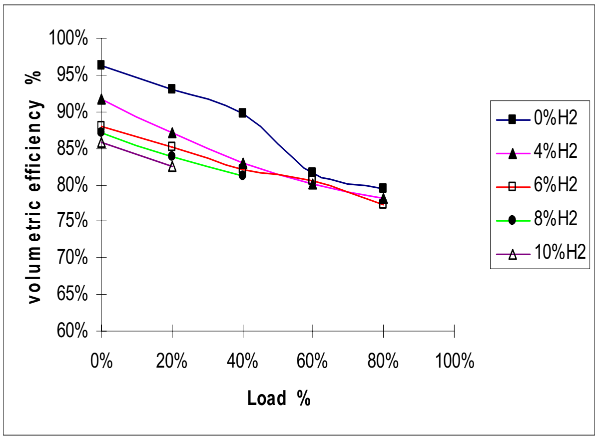

Fig. 7 Effect of load on the volumetric efficiency for different hydrogen blending ratios at 1250 rpm

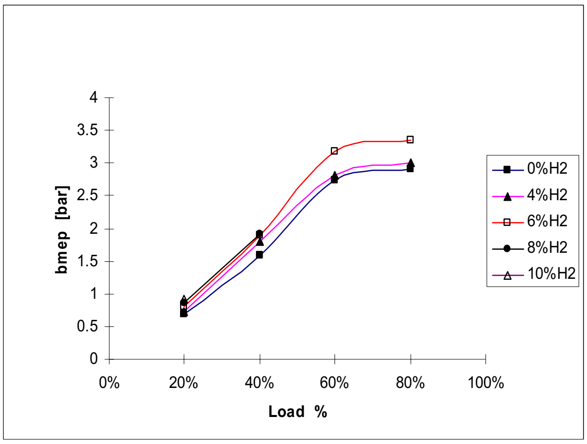

Fig. 8 Effect of load on bmep for different hydrogen blending ratios at 1250 rpm

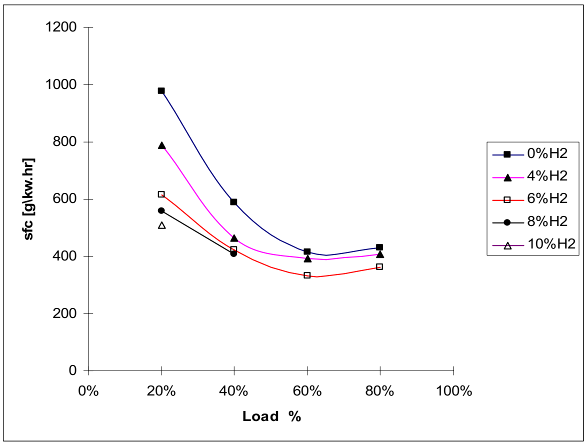

Fig. 9 Effect of load on sfc. for different hydrogen blending ratios at 1250 rpm

Figs. 10, 11, 12 and 13 show the effect of the load at different hydrogen blending ratio on the thermal efficiency ,volumetric efficiency, brake mean effective pressure and specific fuel consumption, respectively . The results are at a constant engine speed of 1500 rpm .These figures show same trends for all plotted variables but at different values.

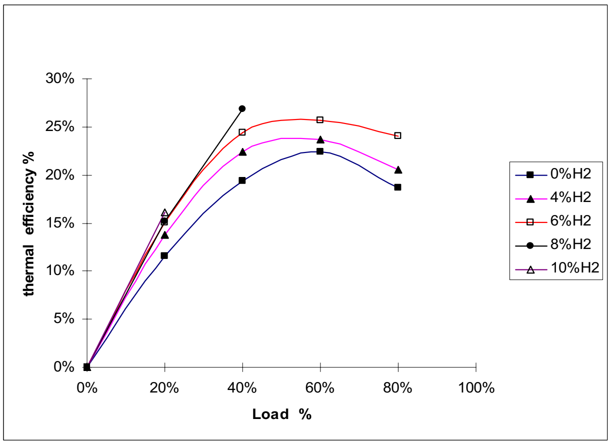

Fig. 10 Effect of load on the thermal efficiency for different hydrogen blending ratios at 1500 rpm

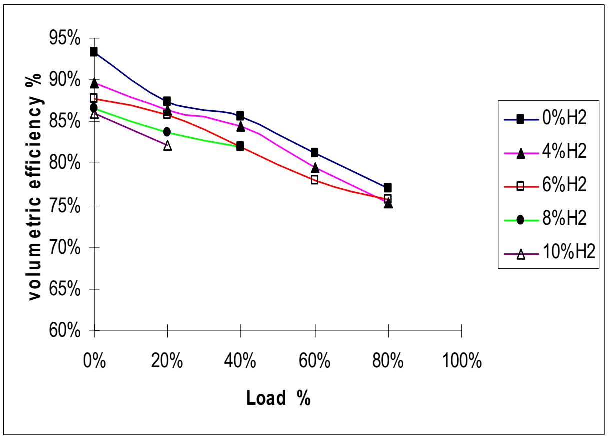

Fig. 11 Effect of load on the volumetric efficiency for different hydrogen blending ratios at 1500 rpm

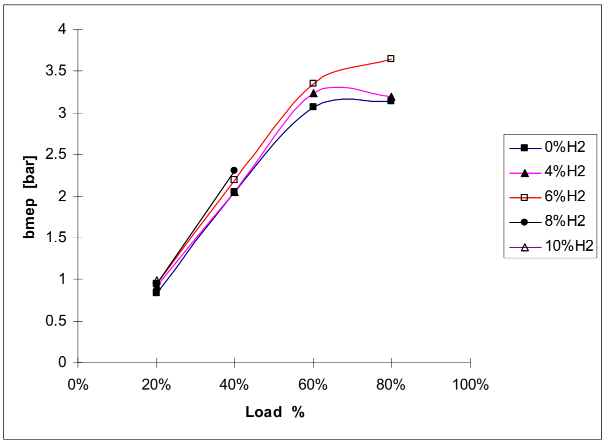

Fig. 12 Effect of load on bmep for different hydrogen blending ratios at 1500 rpm

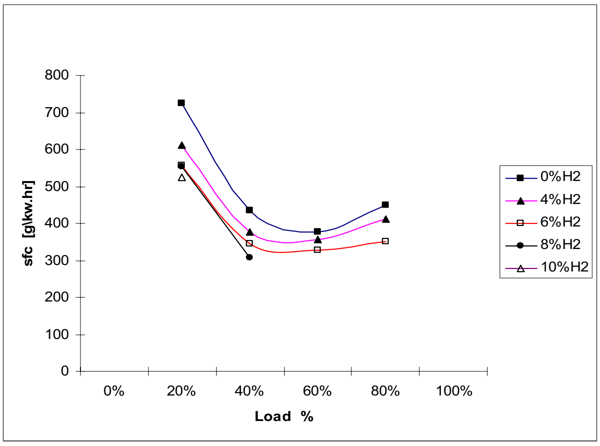

Fig. 13 Effect of load on sfc for different hydrogen blending ratios at 1500 rpm

Figs. 14, 15, 16 show the effect of the engine speed at different hydrogen blending ratio on the thermal efficiency , mean effective pressure and the specific fuel consumption , respectively . The results are at 20% load condition. The thermal efficiency for all hydrogen blending ratios increases with increasing engine speed at constant load due to better combustion process .

The brake mean effective pressure for all hydrogen blending ratios increases with increasing engine speed at constant load due to increases the power caused by better mixing process. The specific fuel consumption decrease with speed for all hydrogen blending ratios due to the improvement in developed power as the engine speed increases.

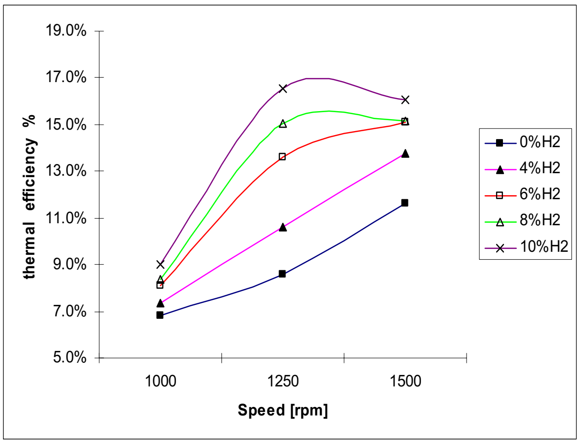

Fig. 14 Effect of speed on thermal efficiency for different hydrogen blending ratios at 20% load

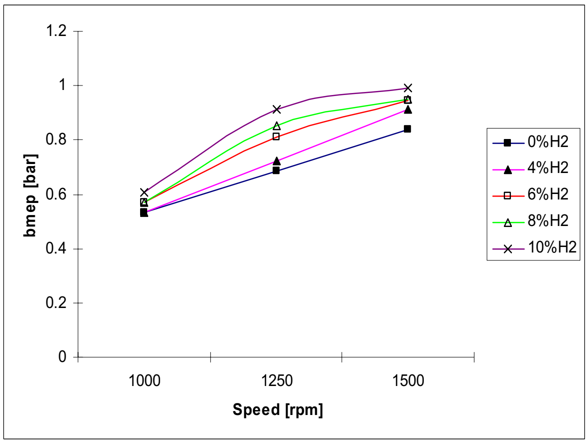

Fig. 15 Effect of speed on bmep for different hydrogen blending ratios at 20% load

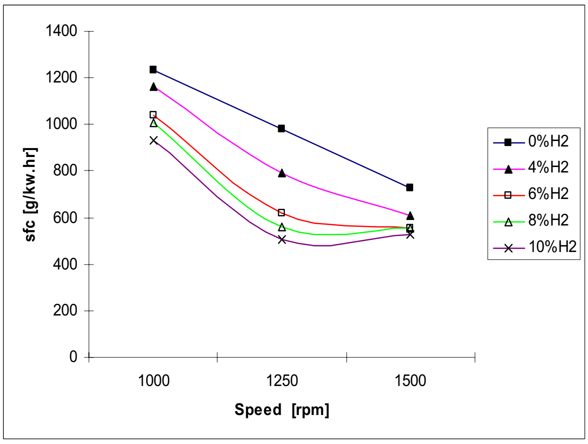

Fig. 16 Effect of speed on sfc for different hydrogen blending ratios at 20% load

IV. CONCLUSIONS

The following conclusions can be drawn from the results of this work:

1. The combustion process is improved as the hydrogen blending ratio increases .
2. The blending ratio of 10% by energy of hydrogen gives the maximum improvement in engine efficiency increases by 40%.
3. The blending with hydrogen reduces volumetric efficiency.
4. The blending ratio of 10% hydrogen gives the maximum reduction in sfc by about 35%.
5. The blending ratio of 10% by energy of hydrogen gives the maximum improvement in bmep which is about 25%.

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TABLE 1
NOMENECLATURE

symbol	meaning	units
$\dot{m}_d$	mass flow rate of diesel fuel	kg/sec
V	volume of diesel fuel consumed during time (t).	m^3
ρ_d	density	kg/m^3
T	time	Sec
V	dynamometer voltage	V
I	dynamometer current	A
$\dot{V}_a$	volume flow rate of air	m^3/sec
$\dot{V}_{H_2}$	volume flow rate of hydrogen	m^3/sec
$\dot{m}_{H_2}$	mass flow rate of hydrogen	kg/sec
$(LCV)_{H_2}$	lower calorific value of hydrogen	kJ/kg
$(LCV)_d$	(lower calorific value of diesel fuel	kJ/ kg
sfc	specific fuel consumption	kg/kW.hr
P	power	kW
η_{th}	engine thermal efficiency	
$\dot{Q}$	rate of heat input	kJ/sec
$\dot{V}_{dis}$	volume displaced per second	m^3/sec
η_v	engine volumetric efficiency	
bmep	brake mean effective pressure	kPa