

Experimental Study of Hydrogen Addition Impact on Emissions and Performance of a Natural Gas Fueled Engine

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Abstract

Hydrogen is seen as one of the important energy carriers of the future with potential to reduce local as well as global warming. The main by-product of the combustion of hydrogen in air is water vapor and trace quantities of oxides of nitrogen. An experiment was conducted to study the impact of hydrogen/natural gas blends on performance, thermodynamic efficiency and exhaust gas emissions in a reciprocating four stroke cycle engine. For this purpose a four-stroke, 4.2 L, V-6 naturally aspirated natural gas engine was used. This engine was coupled to an eddy current wet type dynamometer. First, the engine was tested with natural gas to develop a baseline for comparison with hydrogen/natural gas fuel blends. A test matrix was used to that included variation of engine load and air-to-fuel ratio. The engine was tested at throttle openings of 50% and 100% and equivalence ratios of 1.0 (stoichiometric) and 0.9 (lean) for hydrogen percentages of 10%, 20% and 30% by volume. The test results showed a reduction in NO_x and CO for most of the cases. The engine power and torque slightly decreased when the hydrogen concentration was increased. This paper fully describes the test setup, the test matrix, and the test procedures. The results are fully analyzed and presented to illustrate the impact of hydrogen-enhanced natural gas fuel blends on engine performance and emissions.

Keywords: Hydrogen, Thermodynamic Efficiency, Natural Gas Engine, Engine Performance, Emissions

1. Introduction

■ The increasing levels of greenhouse gases combined with increasing world oil prices and demand have created a need for clean alternative fuel power system. Hydrogen can be one of the alternative forms of clean and environmental friendly fuel. Hydrogen is an abundantly available renewable resource and can be produced by reformation of water, natural gas and coal gasification. Research is done in coal gasification techniques, which produce not only cleaner electric power, but also substantial amounts of hydrogen. Combustion of hydrogen in air produces water vapor, traces of oxygen if lean burned and traces of thermal nitrous oxide. Recent studies show that the desirable combustion properties of hydrogen make it the most likely candidate to eventually replace petroleum fuels [1]. Internal combustion engines fueled by compressed natural gas are operated in variety of industries. Hydrogen-supplemented engine operation presents a viable mid-term solution for the transition from conventional petroleum-based fossil fuels to hydrogen. An added benefit of hydrogen dual-fuel engine operation is that the process requires minimal redesign of conventional engines in order to operate with hydrogen supplemented fuel mixtures.

Performance, efficiency and power of internal combustion engines can be improved by increasing compression ratio and by lean operation. But research done by Caris and Nelson [2] on V8 spark ignition engine shows limited benefit in thermal efficiency if compression ratio is increased above 17:1. Also increasing compression ratio has limitation in a way of producing more emissions, basically NO_x which is function of temperature. Lean operation results in considerable reduction of laminar flame velocity, which will result in misfire and/or incomplete combustion. The excellent combustion properties of hydrogen make it a prime candidate for use as a fuel in dual fueled and single fueled internal combustion engines. Karim et al. [3] investigated the properties of various methane-hydrogen fuel mixtures and the impact of these mixtures on overall engine performance, combustion, and emissions. Bade-Shrestha and Karim [4] investigated the performance implications of the addition of hydrogen to methane-fueled spark ignition internal combustion engines. The addition of hydrogen to methane was found to enhance performance, particularly during operation with lean mixtures. The lean limit for methane-air compression engine is around 0.53, this limit can be further lowered by addition of hydrogen that has very wide range of flammability (lower limit 4% and upper limit 75%) in air. In addition, hydrogen has a laminar burning velocity five times that of methane at stoichiometric condition, which results in more of isochoric process [5]. Also ignition energy for hydrogen is 7.14% that of methane thus resulting in complete combustion of lean charge. This along with small quenching distance results in pre-ignition and backfire. Backfire and pre-ignition can be reduced by in-cylinder injection, exhaust gas recirculation, sequential timed injection [5] and blending natural gas with hydrogen. Hydrogen has also high autoignition temperature, which results in use of higher compression ratio as compared to natural gas without any danger of knocking, which results in increase of thermodynamic efficiency.

The objective here is to study experimentally the impacts of hydrogen/natural gas blends on a conventional natural gas engine emissions and performance. A detailed test matrix was developed so as to investigate effect of hydrogen/natural gas blends on the emissions and efficiency at part and full load, and equivalence ratios of 1.0 (stoichiometric) and 0.9 (lean). Hydrogen percentage was varied from 10% to 30% by volume. The results showed reduction in power and torque for most of the cases. Engine exhaust gas emissions were found to be reducing for all percentage of hydrogen for 0.9 equivalence ratio. These results were further analyzed so as to find the optimum hydrogen/natural gas blends that would reduce emissions and improved engine efficiency.

2. Experimental set-up

A four-stroke naturally aspirated natural gas engine is used to study the impacts of hydrogen/natural gas blends on reciprocating internal combustion engine. Table 1 gives the details of the engine.

Fig. 1 shows a schematic of the experimental set-up, in which the pipeline from high pressure hydrogen bottle and high pressure natural gas from compressor are connected to the blending chamber. Premixing of hydrogen with methane is based on Dalton's law of partial pressure. First the blending chamber is filled with natural gas to a pressure depending on the hydrogen percentage by volume. Then, hydrogen was added. After each set of experiments, the blending chambers were purged with natural gas for several times.

The engine is coupled with an eddy current dynamometer. The engine speed was controlled by a dynamometer controller and hence changing load on the engine. The engine speed and torque was measured using magneto-pickup and load cell, respectively. Fuel and air flow to the engine is measured by an orifice plate and a laminar flow element, respectively. Exhaust temperature is measured with the help of K-type thermocouple placed in the exhaust manifold. A 4-gas portable emission analyzer (TSI series CA-6300, model CA-6315) is used to measure the engine exhaust gas emissions such as CO , NO , O_2 , and NO_2 . An algorithm was developed using OPTO 22 (An OPTO 22 SNAP Ethernet I/O system is used to digitize and transfer data into the computer) so as to measure the instantaneous air and fuel flow at ambient condition with corresponding air-to-fuel ratio.

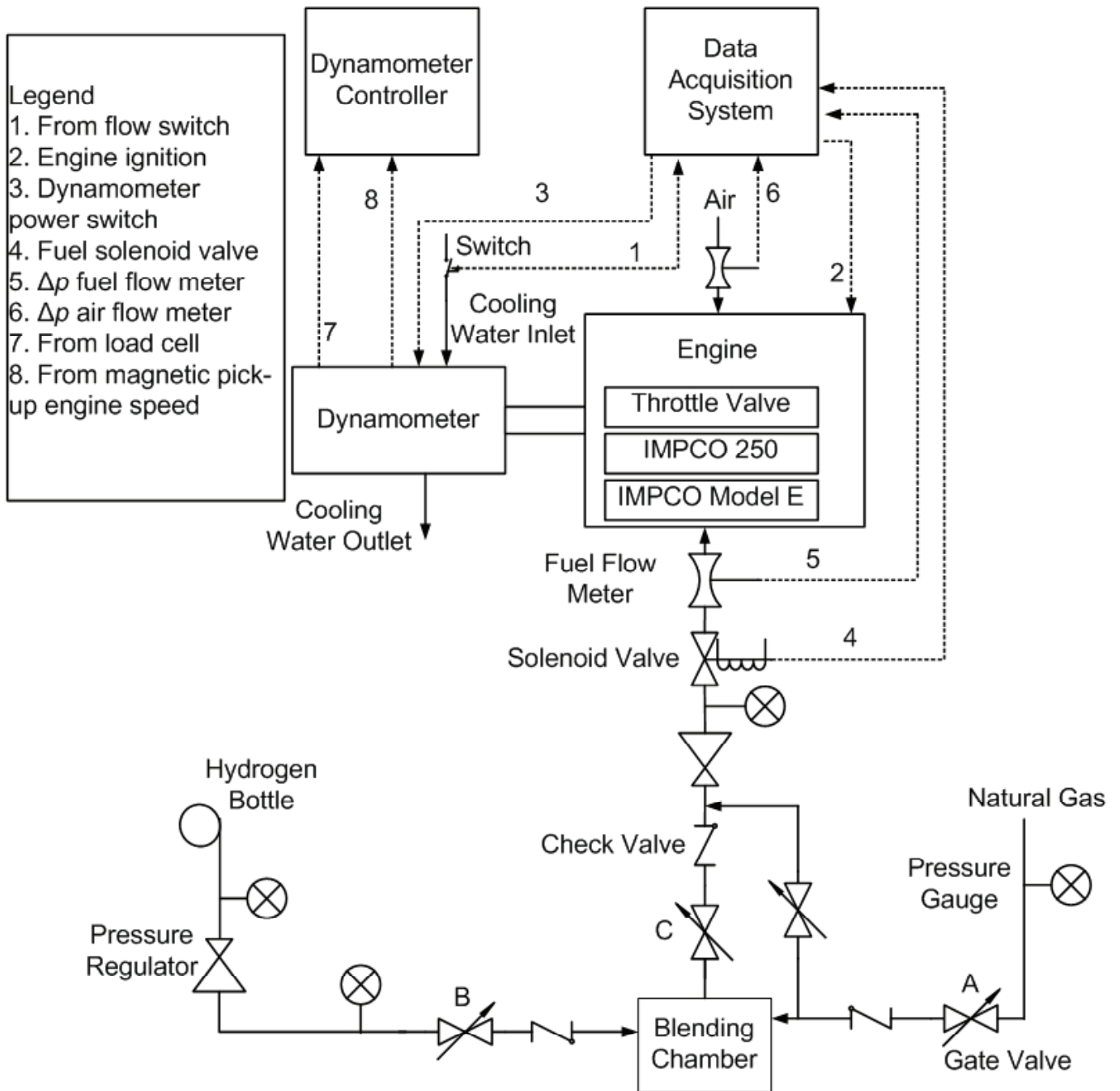


Fig. 1. Schematic of the experimental set-up

3. Test Matrix

A test matrix was created that is comprised of two phases. The first phase examines the emissions and efficiency of the engine operating with pure natural gas as a fuel to establish baseline engine parameters. In the second phase, the engine is tested with different concentrations of hydrogen and natural gas mixture. The data thus obtained is compared to the data obtained during the first phase. According to Larsen [6], the main parameters that affect engine efficiency and emissions are engine type, engine speed (N), engine load (τ), air-fuel equivalence ratio (ϕ), ignition timing (IT), atmospheric conditions, and fuel type. As shown in table 2 these parameters were considered while developing a test matrix so as to minimize the variables. As the engine speed and load changes, the Engine Performance Module, EPM, alters the spark timing and air-to-fuel ratio in the case of closed loop operation. In doing so the air-fuel ratio constantly oscillates between rich and lean of stoichiometric value. These dynamic conditions introduce new variables like throttle position and fuel flow, and hence the fluctuations in the equivalence ratio.

As already stated above, the engine under consideration is naturally aspirated conventional natural gas engine. The operating range of speed for the engine under consideration is 800 to 3000 rpm. As this engine is used for stationary application, it is expected to operate in the speed range around maximum torque, hence the engine speed of 1800, 2200 (maximum torque as per manufacturer) and 2600 rpm was selected for test. The engine load was varied by changing the throttle valve position, for which 50% and 100% throttle opening was considered. So as to study the impact of hydrogen addition at lean and stoichiometric condition air-fuel equivalence ratios of 1.0 (stoichiometric) and 0.9 (lean) was finalized. At any given equivalence ratio the ignition timing was adjusted so that the engine develops maximum output torque. The in-cylinder peak pressure as well as the peak combustion gas temperature are the highest at this point, and produce the highest quantity of pollutants [7]. The data thus obtained was corrected to standard condition of 70 °F and 29.92 inch HgA. Fuels blends of 0%, 10%, 20% and 30% hydrogen in natural gas by volume were tested [8].

4. Test procedure

4.1. The procedure followed for testing the engine with natural gas is as follows:

1. Start the engine with no load and run it at an idle speed of approximately 800 rpm.
2. Allow the engine to reach a steady state operating condition. The steady state condition is defined here as when the cylinder head and the coolant discharge temperatures varied less than 1°F over a period of five minute and remains constant. These readings were monitored from the EPM.
3. Set the engine speed (1000, 1400, 1800, 2200, 2600 and 3000 rpm) and throttle opening position (50 and 100%) to the desired value. The engine was first tested with the throttle opening varying from 25%, 50%, 75% and 100%. It was observed that there was not a significant difference in the engine

power, torque and emissions data for throttle opening of 75% and 100% and also engine operation was not smooth at 25% throttle opening. Hence, it was decided to carry on the engine tests only for 50% and 100% throttle opening positions.

4. Set the fuel flow rate for a specified equivalence ratio. Then, adjust the spark timing so that engine develops maximum output torque.

5. Collect the baseline data at the specified throttle opening position, equivalence ratio and spark timing. The data include the engine speed, load, air flow rate, fuel flow rate, atmospheric temperature and pressure, manifold pressure, coolant temperature, head temperature, manifold temperature, intake air temperature, ignition timing, and the exhaust gas concentrations of oxygen, carbon monoxide, and nitrogen dioxide.

6. The gas analyzer probe must be placed before the catalytic converter, so as to nullify the effect of the catalytic converter on emissions.

7. Repeat all the tests at least two times to evaluate repeatability and to validate the data.

4.2. The procedure for testing the engine with blended fuel is as follows:

1. Start the engine with no load and run at idle speed with pure natural gas.
2. Allow the engine to reach a steady state operating condition.
3. Gradually increase the engine speed and equivalence ratio to the target values and then adjust the spark timing according to the baseline value.
4. Switch the engine fuel from the pure natural gas to the hydrogen/natural gas blend and allow the engine to again reach a steady state operating condition.
5. Follow the baseline test procedure from step 3 to step 7
6. After each test the storage fuel tanks were purged several times with natural gas to make sure the existing gas concentration would not influence the concentration of the newly filled mixture

5. Data analysis

The test plan had to be modified because of some issues occurred during the engine testing with hydrogen/natural gas blends. These modifications are as follows

1. Testing the engine with 100% throttle opening and 30% hydrogen concentration was eliminated because of the spark plugs failure which caused the engine to backfire.
2. CO emissions for this engine were found to be very sensitive to equivalence ratio close to stoichiometric condition. For instance, with small change in equivalence ratio, say changing from 0.995 to 1.0 the variation in CO was very high. Hence it was decided to test the engine at equivalence ratio of 0.90 only with throttle openings of 50% and 100%.

At least two sets of experiments were conducted for each test point. The measured load values were corrected to the standard conditions of 70 °F and 29.92 inch HgA. The measured data analyzed in this paper is an average value of the collected data set for equivalence ratio of 0.9 and throttle openings of 50% and 100%.

Fig. 2 and 3 show the variation of engine torque with engine

speeds for 50% and 100% throttle openings, respectively. It can be seen from the graphs there is not much of difference in measured torque for 10%, 20% and 30% hydrogen concentration by volume. A maximum reduction of 1.5% was measured for 30% hydrogen and 50% throttle opening. This might be due to the lower volumetric heating value of hydrogen associated with increasing the hydrogen concentration hydrogen/natural gas blends. Similar results have been published by Shrestha et al. [4]. Also Bauer [9] reported reduction in power of about 8% with 60% hydrogen/natural gas blend.

Figs. 4 and 5 show the variation of carbon monoxide (CO) emissions with engine speeds for 50% and 100% throttle openings, respectively. CO emissions measured at equivalence ratio of 0.9 are higher for 50% throttle opening as compared to 100%. This can be attributed to decrease in cylinder temperatures and pressures associated with closing throttle opening [9]. The measured values of CO emissions reduced for both cases as the hydrogen concentration is increased. This might be due to the absence of carbon atoms in hydrogen fuel and thereby lowering hydrocarbon concentration in the fresh charge with increase in hydrogen percent. A maximum reduction of 36% in CO emissions was measured at 30% hydrogen concentration and 2,600 rpm. After doing statistical analysis it can be concluded that for equivalence ratio of 0.9 and 50% throttle opening the reduction in CO emissions associated with increase in hydrogen/natural gas blend from 20% to 30% is not significant. For example the minimum difference in percentage reduction of CO emissions between 20% and 30% hydrogen/natural blends is about 0.13%. Increase in hydrogen percentage results in increase in combustion temperature, furthermore according to Lefebvre [10] significant amounts of CO will also be present due to the dissociation of CO_2 at high temperature.

Similar results were measured by Van Blarigen et al. [11], Verstraeten et al. [12], Bauer et al. [9], and Ally et al. [13]. At full load Paul et al. [14] reported CO emission reductions of about 40% for hydrogen/natural gas blend of 30% and 55% at part load.

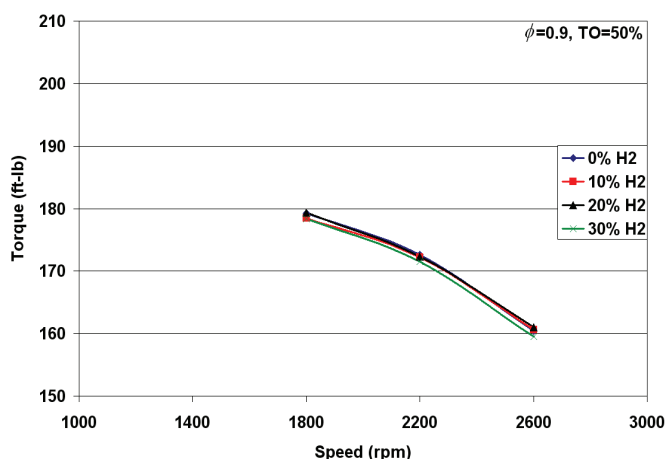


Fig. 2. Variation of torque with speed for ϕ 0.9 and 50% throttle opening

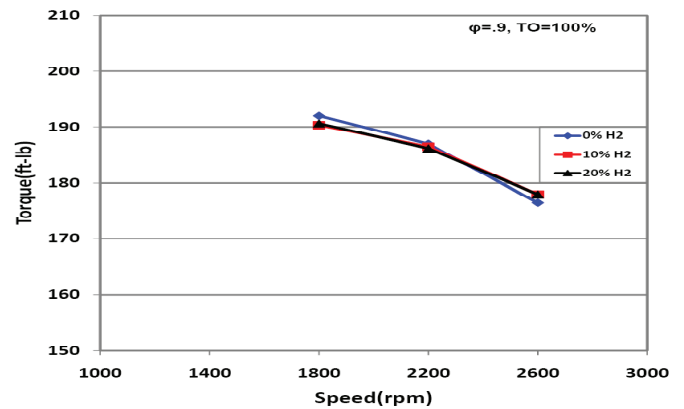


Fig. 3. Variation of torque with speed for ϕ 0.9 and 100% throttle opening

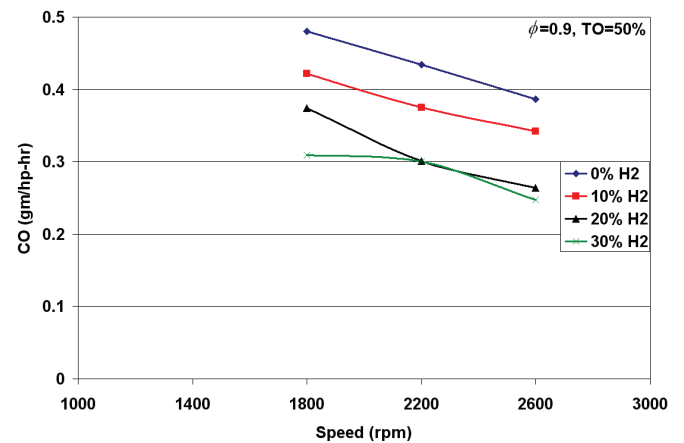


Fig. 4. Variation of CO emissions with speed for ϕ 0.9 and 50% throttle opening

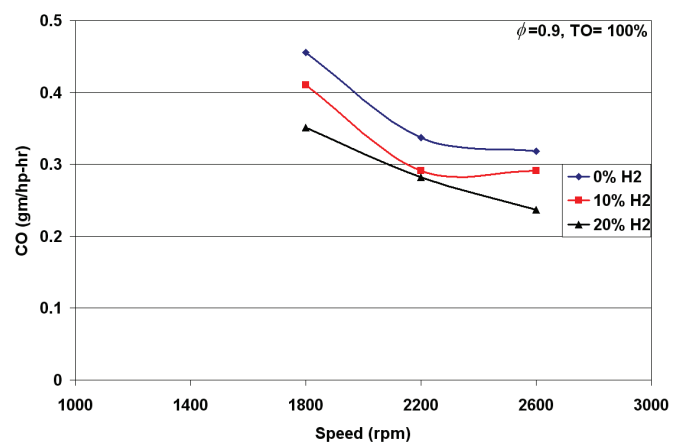


Fig. 5. Variation of CO emissions with speed for ϕ 0.9 and 100% throttle opening

Figs. 6 and 7 show the variation of NO_x emission with engine speeds for 50% and 100% throttle openings, respectively. The measured value of NO_x, which is the summation of NO and NO₂ was higher for 100% throttle opening as compared to 50% throttle opening. After doing uncertainty analysis (refer to Tables 3 and 4), a reduction in NO_x emissions is measured with increase in hydrogen concentration for both the equivalence ratios when compared with baseline set. For equivalence ratio of 0.9 the maximum reduction in NO_x emissions measured is about 19%, which might be due to the ability of hydrogen to mix with air to form a homogenous mixture because of the higher diffusivity of hydrogen [15]. Furthermore, the higher flame propagation rate of hydrogen effectively reduces the periods of combustion during the expansion stroke [16]. For 50% throttle opening it can be concluded that by increasing hydrogen concentration from 20% to 30% did not reduce NO_x emissions. This might be due to the higher calorific value of hydrogen which increases the amount energy per molar basis and thus increasing the temperature and hence NO_x. For 20% hydrogen/natural gas blend the percentage reduction in NO_x emissions measured for 50% and 100% throttle opening is 13% and 18% respectively.

A reduction in NO_x emission to near zero was measured by Van Blarigan et al. [11] with 30% hydrogen/natural gas blends. Heffle [17] reported reduction in NO_x emissions to about 1 ppm, but with the use of EGR and a three way catalytic converter. Grebig et al. [18] reduced NO_x emissions to almost zero.

Figs. 8 and 9 show the variation of brake specific fuel consumption (BSFC) with engine speeds for 50% and 100% throttle openings, respectively. The BSFC is a measured quantity of fuel required to produce a unit power which is inversely proportional to the brake thermal efficiency (BTE) and lower heating value and is given by.

$$\eta_{BTH} = \frac{1}{BSFC \times Q_{HV}}$$

where;

η_{BTE} = Brake Thermal Efficiency

Q_{HV} = Heating Value of Fuel

The measured values of BSFC for 50% and 100% throttle opening decreases with increase in hydrogen percentage, because of higher energy contents of the fuel associated with increasing hydrogen concentration. Also it could be seen from these plots that BSFC is increased with speed, this might be due to the higher frictional power at higher speeds. The maximum reduction calculated for BSFC with addition of hydrogen is about 7% and 9% for 50% and 100% throttle opening respectively. Similar reductions were reported by Bauer [9] and Anderson [19].

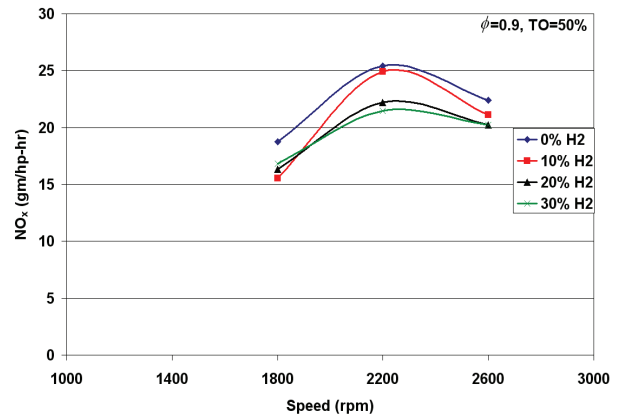


Fig. 6. Variation of NO_x emissions with speed for ϕ 0.9 and 50% throttle opening

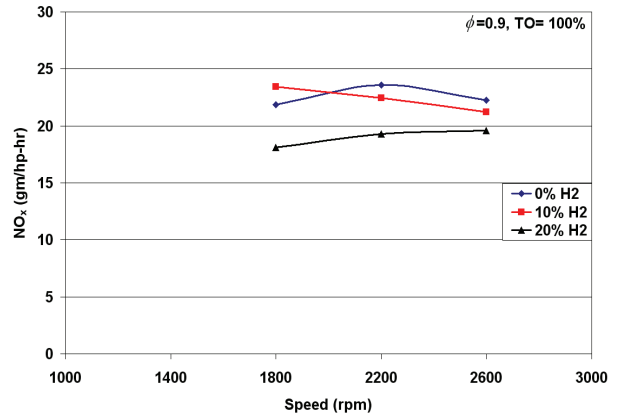


Fig. 7. Variation of NO_x emissions with speed for ϕ 0.9 and 100% throttle opening

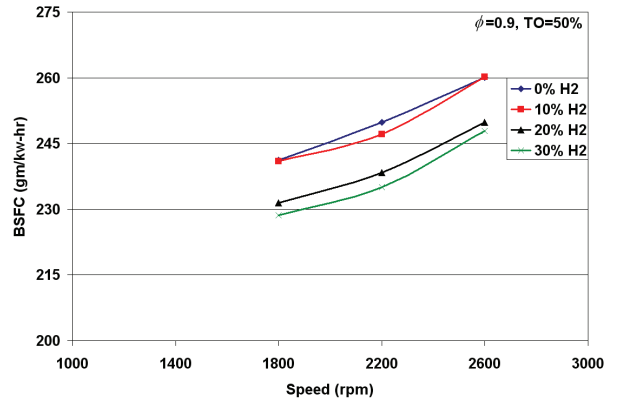


Fig. 8. Variation of BSFC with speed for ϕ 0.9 and 50% throttle opening

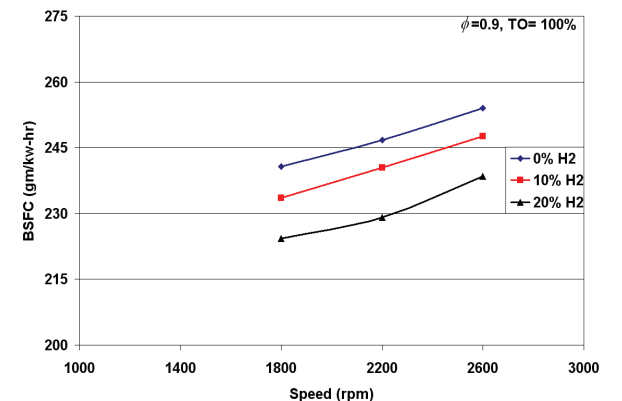


Fig. 9. Variation of BSFC with speed for ϕ 0.9 and 100% throttle opening

Anderson [19] stated the gross indicated efficiency depends on several factors. First, the increased amount of hydrogen leads to an increased burn rate which is beneficial for efficiency. Second, adding hydrogen improves the combustion efficiency to some degree. Third, the ratio of specific heats of the burned gas goes up with increased amount of hydrogen. From these discussions one can conclude that adding 20% hydrogen by volume reduces emissions with little effect on engine performance.

Further investigation was carried on to find the impact of the ignition timing on the emissions and performance for the engine with 20% hydrogen for the following reasons. First, retarding the spark timing towards TDC increases the charge temperature during flame initiation and propagation, and speeds up the reactivity of the mixture when it contains a high concentration of hydrogen [20]. Second, the laminar flame speed (S) which is proportional to the square root of the reaction rate (ω) as shown by [21]:

$$S = \left(\frac{\lambda \omega}{C} \right)^{0.5}$$

where;

λ = average thermal conductivity

C = average specific heat

Blending methane with hydrogen increases flame temperature and also supply of active radicals which results in increasing the laminar flame speed. Thereby increasing the low laminar flame velocity of methane. Many researchers have also reported that NO_x formation is a function of combustion temperature and residence time. Attar [20] reported that the NO_x emissions reduction associated with retarding the ignition timing is due to the reduction in combustion duration and hence residence time.

The ignition timing of the engine was varied to study the effect on engine performance as well as the emissions. First the ignition timing was retarded by 5° relative to the initial position. After getting some promising results it was decided to alter the ignition timing until the difference in NO_x emissions between the two consecutive points (ignition time) not vary much in the range of 600–700 ppm and also the engine torque reduction should be less than 5%. The ignition timing was only altered for an equivalence ratio of 0.9 for 20% hydrogen/natural gas blend and throttle openings of 50% and 100%.

Tables 3 and 4 show the percentage reduction (+ sign indicates percentage increase) with reference to its baseline values for BSFC, torque, and exhaust gas emissions (NO_x and CO) with throttle opening of 50% and 100% respectively.

Based on the results shown in the tables 3 and 4 the following outcome can be summarized;

1. For equivalence ratio of 0.9 and 50% throttle opening
 - a. Maximum reduction in BSFC of about 5%.
 - b. Maximum reduction in torque of about 4%.
 - c. Maximum reduction in NO_x and CO emissions of about 66% and 38% respectively.

2. For equivalence ratio of 0.9 and 100% throttle opening
 - a. Maximum reduction in BSFC of about 9%.
 - b. Maximum reduction in torque of about 6%.
 - c. Maximum reduction in NO_x and CO emissions of about 61% and 31% respectively.

6. Conclusion

Based on this experimental work it can be concluded that blending natural gas with hydrogen is one of the viable solutions for this engine to reduce the exhaust gas emissions without significant loss of its performance. Further reduction in emissions in the range of 20–28% for CO and 60–65% for NO_x can be obtained by retarding the ignition timing. However, this will reduce the torque by about 5% and BTE by about 2%.

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TABLE 1. The engine specifications

Details	Description
Engine type	V-6
Bore and stroke	3.18 in X 3.74 in
Capacity	4195 cc
Compression ratio	9.3:1
Maximum speed	3000 rpm
Throttle control	Electronic

TABLE 2. Test matrix

Throttle Opening	Hydrogen	1,800 rpm	2,200 rpm	2,600 rpm
50%	10%	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$
	20%	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$
	30%	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$
100%	10%	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$
	20%	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$	$\phi=0.9, 1.0$

TABLE 3. Percentage changes for 20% hydrogen with 50% throttle opening

Ignition Timing	Speed	BSFC	Torque	NO_x	CO
baseline	1800	3	0	12	21
	2200	4	0	12	30
	2600	3	0	9	31
Retarded 5°	1800	4	1	36	31
	2200	5	0	34	38
	2600	4	1	31	36
Advanced 5°	1800	2	2	49	28
	2200	2	2	65	21
	2600	1	4	66	6

TABLE 4. Percentage changes for 20% hydrogen with 100% throttle opening

Ignition Timing	Speed	BSFC	Torque	NO _x	CO
baseline	1800	8	0.5	17	23
	2200	8	0	18	16
	2600	6	1	12	25
Retarded 5°	1800	9	4	26	31
	2200	7	3	38	26
	2600	6	1	33	28
Advanced 5°	1800	4	5	58	19
	2200	3	6	61	22
	2600	4	3	60	17

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