

Development of Hydrogen Fuelled Low NO_x Engine with Exhaust Gas Recirculation and Exhaust after Treatment

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ABSTRACT

Air pollution caused by vehicular tail pipe emissions has become a matter of grave concern in major cities of the world. Hydrogen, a carbon free fuel is a clean burning fuel with only concern being oxides of nitrogen (NO_x) formed. The present study focuses on the development of a hydrogen powered multi-cylinder engine with low NO_x emissions. The NO_x emissions were reduced using a combination of an in-cylinder control strategy viz. Exhaust Gas Recirculation (EGR) and an after treatment method using hydrogen as a NO_x reductant. In the present study, the low speed torque of the hydrogen engine was improved by 38.46% from 65 Nm to 90 Nm @ 1200 rpm by operating at an equivalence of 0.64. The higher equivalence ratio operation compared to the conventional low equivalence ratio operation lead to an increase in the torque generated but increased NO_x as well. The back fire at higher equivalence ratios was prevented by cold EGR operation while maintaining conditions to prevent water condensation. The spark timing was varied between 2°-15° BTDC and the variation in torque with and without EGR was investigated. The spark timing was found to be advancing with increasing EGR concentration. In the present work, parameter optimization was carried out to generate a peak torque of 180 Nm @ 3600 rpm and a maximum power of 67 kW @ 3600 rpm. The NO_x emissions were further reduced by catalytic after treatment. A NO_x reduction of upto 20% was obtained due to unburned hydrogen in the exhaust stream. Further studies are being carried out to enhance the NO_x reduction capability.

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INTRODUCTION

The air quality degradation in major cities around the world has raised alarms. The International Energy Agency ranks air pollution as the fourth largest health risk to humans. According to their report, 92% of the global energy production depends on combustion [1]. Transport and power generation sectors are the major sources of oxides of nitrogen (NO_x). Exhaust emissions from vehicles are a major concern as they emit these pollutants directly into the air in populated regions. Additionally, the pollutants are emitted close to the ground level, due to which the exposure to inhabitants is very high as compared to other sources of pollution [1]. Under these circumstances, the adoption of clean burning fuels in the transport sector has become the necessity for a sustainable future.

Among the many alternative sources of fuel under consideration, hydrogen holds a vital position. Hydrogen was proposed as the most promising clean and abundant source of energy capable of providing a permanent solution to all the environmental problems caused by fossil fuel applications. This idea was formally presented at 'The

Hydrogen Economy Miami Energy' (THEME) Conference, 1974 [2]. The idea of hydrogen as a fuel for the internal combustion engines caught the attention of researchers all over the world decades ago as reported in detail by Das [3]. Automotive companies like Ford Motor Company, BMW, Mahindra & Mahindra etc. have developed hydrogen operated engines. Ford developed a 2.0 litre engine fueled with hydrogen meeting the SULEV standards [4]. BMW introduced its hydrogen engine in the 7 series vehicle. It was a 6.0 litre V12 bifuel (gasoline- hydrogen) engine which operated with liquid hydrogen stored on board [5]. Mahindra & Mahindra developed a single cylinder 395 cc hydrogen fuelled engine operating under lean conditions. The engine developed 25% less power compared to its gasoline counterpart at full load conditions and an equivalence ratio of 0.6 [6].

The utilization of hydrogen as an automotive fuel requires certain modifications to be carried out on an existing engine. The unique properties of hydrogen as given in Table 2 warrant for these modifications. For reference, the properties of CNG are also given in the table.

Table 1. Property comparison between CNG and H₂

Property	CNG	H ₂	Effect on engine
Stoichiometric AFR	17.2	34.3	Affects volumetric efficiency
LHV (MJ/kg)	50	120	Very high energy content on mass basis
Octane number (RON)	>120	>130	Higher compression ratio can be used
Minimum ignition energy (MJ)	0.2	0.02	Ignition system with low residual energy
Laminar flame speed (m/s)	0.45	1.9-3.2	Near to ideal (isochoric) combustion
Flammability limits %	5.3-15	4-75	Lean air-fuel ratio can be used
Auto-ignition temperature (°C)	540	585	Safer fuel / knock resistance

Homan [7] experimentally found that the high auto ignition temperature of H₂ implies that an ignition source needs to be present for the combustion to initiate, as even high compression ratios fail to attain this temperature by compression alone. The low density of hydrogen necessitated the use of injectors which can deliver high flow rates of hydrogen. The low ignition energy implies that the ignition system needs to be specifically designed to achieve a low residual energy. The low ignition energy for H₂ operation could cause backfire, which takes place due to the combustion of hydrogen fuel in the intake manifold with the aid of energy sources nearby [8]. The energy sources could be hot spots formed from any deposits or hot sparkplugs or valves. With appropriate modifications, hydrogen engine can operate without back fire even at high equivalence ratios. Verhelst et al. [9] reported that engine operation at stoichiometric conditions and rich conditions without combustion anomalies are possible.

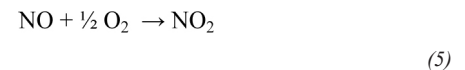
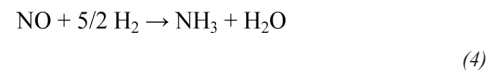
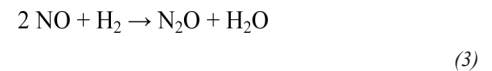
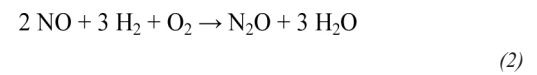
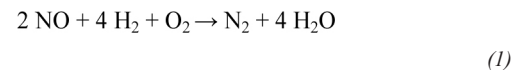
In the present study, a multi-cylinder internal combustion engine (ICE) is optimized for hydrogen operation. Hydrogen ICEs have a very strong power output versus NO_x emissions trade-off. The NO_x emissions of a hydrogen internal combustion engine are inherently low when operated at very lean conditions, i.e., using excess air for charge dilution [3]. This lean-burn fuel metering strategy also causes a considerable reduction in torque. The increase in equivalence ratio leads to an increased torque but also results in an exponential rise in NO_x emissions, as reported by Das [8]. The NO_x formation in Internal Combustion (IC) engines is guided by the Zeldovich mechanism. NO_x formation occurs at temperatures above 1500 °C, and the rate of formation increases rapidly with increasing temperature [10]. Several researchers have overcome this increased NO_x emission effect by employing strategies like the Exhaust Gas Recirculation (EGR) [11, 12, 13, 14, 15, 16]. The presence of water vapour in the intake leads to the reduction of flame speed and the reduction of NO_x. The NO_x reduction achieved depends directly on the specific heat of the diluents [13]. The diluents' heat capacity varies with its specific heat and mass flow rate and dictates the NO_x reduction achieved.

Szwaja et al. [15] developed a strategy of estimating EGR for the naturally aspirated, hydrogen fuelled engine. The EGR was calculated online on the basis of oxygen content in exhaust gases and oxygen content in the intake manifold. Both oxygen concentrations were measured by wide-band electrochemical lambda sensors (UEGO

sensor) installed at the appropriate positions. Verhelst et al. [16] described different methods to calculate the amount of EGR in hydrogen fueled ICEs. These methods included a constant volumetric efficiency approach and exhaust oxygen concentration based approach.

Verhelst et al. [17] showed that supercharging the engine results in an increase in power output, and the combination of supercharging with EGR permits stoichiometric operation of the engine leading to improved power output. Natkin et al. [18] reported that EGR strategy could produce 23%-29% more torque than the lean-burn strategy.

High equivalence ratio operation leads to high NO_x formation and EGR strategy alone may not be sufficient for NO_x reduction. Polychronopoulou et al. [19] discussed the application of hydrogen as a reductant for the Selective Catalytic Reduction (SCR) of NO_x. It was reported that Pd-based catalysts can result in NO_x conversion and N₂-selectivity values in the 80-95% range depending on factors like the composition of support, promoter, etc. Liu et al. [20] discussed about the NO_x reduction with hydrogen based selective catalytic reduction (H₂-SCR) in the presence of oxygen. The main reactions that could take place during the H₂-SCR are given by Eqs. (1), (2), (3), (4), (5), (6) [20].



Reaction (1) is the ideal step that should be followed for NO_x reduction, since it gives N₂ as the product, whereas other reactions result in N-containing species, which are also considered as pollutants. In the case of hydrogen fuelled vehicle, the pathway of NO_x reduction is with hydrogen based SCR unlike NH₃-based SCR, as the reductant (H₂) is already available onboard. Hamada et al. [21] reported the activity of various catalysts for H₂ SCR under varying compositions with excess oxygen and hydrogen. Based on the studies of Costa et al. [22], they reported that 0.1% Pt/La_{0.7}Sr_{0.2}Ce_{0.1}FeO₃ shows a selectivity of 92% N₂ and 8% N₂O when the inlet gas consisted of 2500 ppm NO, 1% H₂, 5% O₂ and 5% H₂O. These studies showed that with the right catalyst and conditions, hydrogen can be effectively used as a reductant for NO_x even in moist and oxidative conditions.

Verhelst et al. [17] found that if the engine can be operated at slightly rich conditions, the excess of hydrogen can be used for effectively reducing the NO_x in a three way catalytic converter (TWC).

emissions. The hydrogen injected to the exhaust stream before the catalytic converter can act as a reductant in the presence of the appropriate catalyst and temperature conditions. Wallner et al. [23] detected the unburned hydrogen in the exhaust by mass spectroscopy. Scott et al. [24] showed that the unburned hydrogen can be detected using the principle of Gas chromatography (GC) with a thermal conductivity detector (TCD).

In the present study, the focus is to increase the engine torque by increasing the equivalence ratio and simultaneously controlling the NO_x emissions by adopting a combination of EGR and H₂-SCR. The cold EGR strategy was adopted, where the re-circulated exhaust gas was cooled to a particular temperature. The condensation of water vapor was prevented by keeping the EGR temperature above the saturation temperature. To further enhance the NO_x reduction, a conventional TWC was integrated into the system and its performance was studied. Unburned hydrogen was the only species in the exhaust stream which could cause NO_x reduction. The combined effect of EGR and TWC on NO_x emission control was investigated in the present study.

EXPERIMENTAL SETUP

The studies were carried out on a multi-cylinder turbocharged engine. The engine specification is given in Table 2.

Table 2. Engine specifications

Engine	4- cylinder, Inline
Bore x Stroke (mm)	89 x 100
Displacement (cc)	2500
Compression ratio	12:1
Number of valves per cylinder	2

A multi-cylinder diesel engine was chosen for conversion into a hydrogen fuelled engine. A schematic of the experimental set up is given in Figure 1. Necessary modifications were carried out as detailed in the text. The diesel engine was converted to a spark ignition mode with the adoption of spark plug as an ignition initiation source. The spark plugs used were cold rated with Iridium electrode instead of Platinum to avoid backfire. Timed Manifold Injection (TMI) was adopted as the fuel induction technique. The hydrogen fuel was injected in a timed sequence at the manifold during the intake stroke and the premixed air-fuel mixture entered the engine cylinder. The compression ratio was set at 12:1 according to the octane rating of the fuel. A suitable turbocharger was selected to improve air intake ability of the engine and hence increase the volumetric flow rate. The engine was coupled to an eddy current dynamometer for torque measurement; the turbocharged engine had an intercooler to increase the mass flow rate of air. Hydrogen was supplied from a cascade system to the fuel rail at a pressure of 4.2 bar. The hydrogen specific injectors mounted on the fuel rail injected hydrogen into the intake manifold, and the cooled air from inter cooler mixed with hydrogen before entering the engine cylinder. The equivalence ratio of operation (ERO) was monitored with the help of wide band lambda sensor mounted on the exhaust outlet. Other operating variables like engine speed, intake air flow rate, boost pressure, coolant temperature, etc. were monitored using specific sensors.

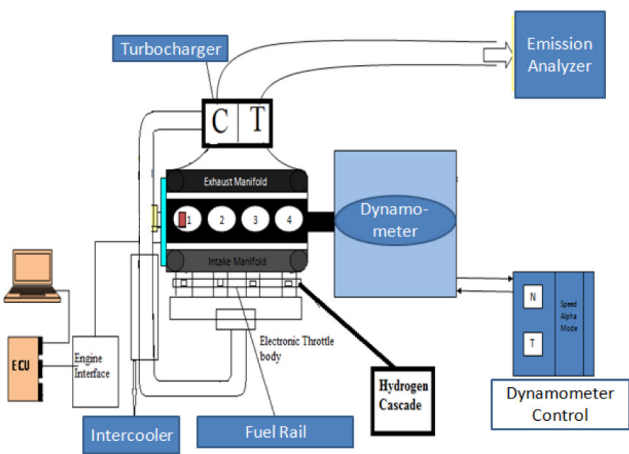


Figure 1. Schematic of the experimental setup

As discussed later, the low equivalence ratio operation resulted in low NO_x emissions but the torque developed under these conditions at low engine speeds was lower than that of high equivalence ratios and high engine speeds. In the present study, the focus was to improve the low speed torque while limiting the NO_x emission levels. The low speed torque could be improved by methods such as (i) operation at high equivalence ratios, and (ii) adopting supercharger for increasing the air flow at low speeds. In the present study, it was proposed to increase the equivalence ratio, i.e., increase the amount of fuel supplied at low speeds. Increasing the equivalence ratio of operation is expected to increase the torque and hence the power output. But this increase in equivalence ratio will expectedly result in increased NO_x emissions, as shown by several studies [8,16]. The drastic increase in NO_x emissions with an increase in equivalence ratio meant the adoption of strategies which could keep the NO_x levels low but at the same time could deliver improved torque. A turbocharged-exhaust gas recirculation (EGR) strategy was proposed coupled with selective catalytic reduction of exhaust with hydrogen acting as the reductant.

The EGR strategy can be adopted in different ways such as (i) cold EGR, and (ii) hot EGR. In cold EGR, the exhaust gas is cooled using an intercooler before entering the engine cylinder, whereas, in the hot EGR strategy, the hot exhaust gas is directly re-circulated from the exhaust port without undergoing any forced cooling. The flow of hot gases in the intake manifold during Hydrogen injection may end up supplying the minimum ignition energy, which could cause backfire. Hence, cold EGR strategy was adopted such that the temperatures of the recirculated exhaust are low. A part of the exhaust gas was recirculated from the exhaust manifold using copper pipes. A heat exchanger was placed at the end of the EGR piping to reduce the temperature. A thermocouple was used to monitor the extent of cooling of the exhaust gas.

In the present study, the exhaust gas contains unburned oxygen, nitrogen, traces of oxides of nitrogen, and water vapour. As expected, the water vapour fraction in the exhaust of our H₂ engine was found to be high in comparison to a conventional gasoline or diesel engine exhaust. Since in this case, one of the major constituents is water vapour, the reduction in in-cylinder temperature is expected to be higher due to the high specific heat of water. The high specific heat capacity of water and its high fraction in the exhaust is expected to