3. LITERATURE SURVEY

3.1 Overview

The use of hydrogen as an alternate fuel source to the automotive industry has been extensively researched. In fact, most of the world's leading automobile manufacturers have committed vast amounts of resources into the development of cars that are powered by hydrogen.

However, the impetus at which these innovations have occurred has increased exponentially over the past few years. This may be attributed, primarily, to the volatility of international crude oil prices, which has a direct effect on the automotive fraternity. Thus, the international community has become alarmingly aware of their total dependence on fossil fuels and the precarious situation in which they may find themselves, should they be "held hostage" by the OPEC nations.

Constant advances in materials and technologies have allowed for the feasibility of systems and concepts, previously deemed ludicrous, to be evaluated as possible design solutions. The generation of materials with superior sealing properties have made past difficulties in the storage of hydrogen obsolete while composite materials have resulted in lighter tanks, thereby reducing the fuel consumption and increasing the range of hydrogen-powered vehicles.

Despite the tremendous progress of the automotive industry towards a hydrogen economy, there exists one inherent problem in the use of hydrogen as an automotive fuel; the fact that it needs to be stored in the vehicle. Unlike conventional fuels, hydrogen is extremely difficult to contain and store. Its small atomic size and low density necessitate the compression of hydrogen into its liquid state for efficient storage.

Most, if not all, of the current hydrogen-powered vehicles contain a stored supply of hydrogen onboard in the form of a hydrogen tank.

The logical next step, therefore, would be the implementation of an onboard hydrogen-generating device with the capability to supply hydrogen as and when it is required by the engine; a so-called “Hydrogen on Demand” system.

This would entail the generation of hydrogen from the electrolysis water or the reformation of natural gas or steam. Also, the effects of fuelling an internal combustion engine on a blend of petroleum and hydrogen are of importance with regard to the expected benefits in employing such a fuel hybrid.

Therefore, the succeeding sections outline and discuss current developments in the use of hydrogen as an alternate fuel and comment on the various automotive projects currently being undertaken. The methods of hydrogen production, as mentioned earlier, are also examined and the viability of each method is discussed.

Finally, a comprehensive review of the literature regarding the fuelling of an engine on hydrogen is presented.

3.2 Industry Developments

3.2.1 BMW Hydrogen

- **History**

BMW's endeavours into the use of hydrogen as the next, and possibly most successful, alternate fuel are extensive, to say the least. Their hydrogen research programs date back to the early seventies and the constant advances in this sphere of their business are testament to the continuous efforts expended in these initiatives.

The first BMW hydrogen-powered vehicle prototype, a 520h, was built in 1979 and was capable of running on both conventional petroleum and hydrogen. The next two decades saw the development of a hydrogen car in every successive generation of the BMW 7-series. Figure 3.1 below, shows BMW's hydrogen fleet throughout their involvement in hydrogen research.

Figure 3.1: BMW's Hydrogen Fleet [4]

Further developments include the BMW 745hl, the "*CleanEnergy*" Mini, and the BMW H2R sports prototype. These will be discussed in detail in the sections that follow.

- **BMW 745hl**

The latest, fifth generation, hydrogen model to be released from the BMW stable is the 745hl. Its 4.4 litre V8 engine is capable of being fuelled with hydrogen or ordinary unleaded petrol.

The 745hl, as illustrated in Figure 3.2, also makes use of BMW's variable valve timing system, *bi-Vanos,* and incorporates variable intake runners (*Valvetronic*) and a fully variable intake manifold. These assist the BMW in reaching a top speed of 215 km/h with a maximum power output of 138 kW as compared to the standard model's top speed of 250 km/h and 245 kW of power [5].

Figure 3.2: BMW 745hl [4]

Driving range is estimated to be 305 kilometres on hydrogen and 640 kilometres on petrol, which allows the 745hl over 900 kilometres between refuelling. Auxiliary features are powered by an auxiliary power unit (APU), which operates via a proton exchange membrane (PEM) supplied directly by a hydrogen feed from the tank. This means that accessories, such as air-conditioning, can be operated independently of the engine [5].

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- **Clean MINI**

Another of BMW’s hydrogen models is the MINI Cooper, Figure 3.3, which runs solely on hydrogen.

Figure 3.3: CleanEnergy MINI Cooper [6]

The hydrogen-powered MINI incorporates new injection technology in that super-cooled liquid hydrogen is injected into the intake ducts where it mixes with the air entering the combustion chamber [5]. The super-cooled air-fuel mixture results in an increased cylinder charge which leads to better engine output and efficiency. Increased performance means that there now exists a hydrogen engine with power delivering capabilities comparable to a standard petroleum-fuelled engine.

Also, the MINI represents a breakthrough in alternative fuel tank technology as its hydrogen tank occupies the same volume and position of the conventional fuel tank, thus eliminating the need for an additional cylindrical tank in the luggage compartment [5].

Other innovations in tank design include the development of a double-core, 25 mm tank wall with 70 alternating layers of aluminium and glass fibre mat, which serve as a thermal insulator to the external environment [7].

The two core layers are separated by a high-vacuum environment, which ensures that the tank contents are extremely well insulated against a rise in temperature and are maintained at -250ºC. The insulation layer, although only 25 mm thick has the equivalent insulation of a 4 m thick polystyrene shield [7].

- **BMW H2R**

The latest and, perhaps, most technologically advanced hydrogen-powered car to be manufactured by BMW, is the BMW H2R (Figure 3.4). Powered by a six litre V12 engine complete with fully variable valve timing, the H2R produces 210 kW and accelerates from zero to 100 $km.h^{-1}$ in six seconds [8].

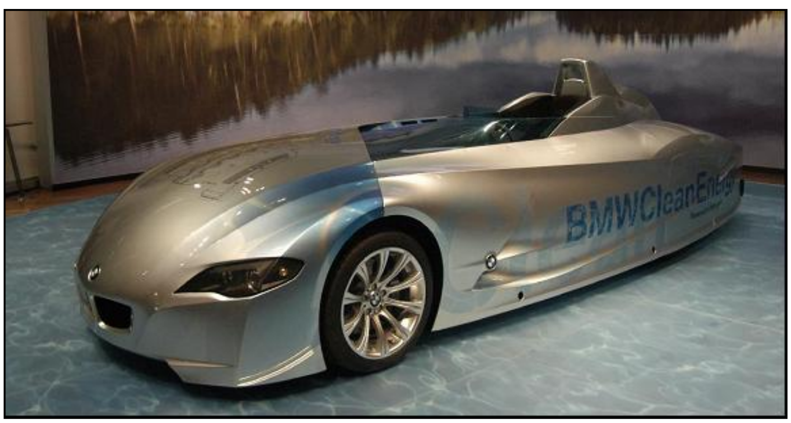

Figure 3.4: BMW CleanEnergy H2R [9]

The H2R holds nine speed records and is testament to the fact that hydrogen-powered sportscars can offer performance on par with their petrol counterparts. This is made possible, largely, by the optimisation of the injection system to meet the specific requirements of hydrogen fuelling.

Unlike standard production engines, where the fuel is supplied directly to the combustion chamber, the valves of the H2R's engine are incorporated into the intake manifold which allows for later injection of hydrogen [8]. Also, the fact that the engine would be operated entirely on hydrogen meant that it could be optimised for the combustion of hydrogen. This includes the use of special valve seat material necessitated by the lack of lubrication of hydrogen fuel.

One of the crucial factors in the optimisation of hydrogen combustion is the faster combustion speed of the hydrogen/air mixture [8]. This means that, for maximum output, the ignition point of the mixture has to be shifted forward to the moment when the piston reached top dead centre (TDC). This ensures that maximum cylinder pressure is attained just as the piston starts to descend.

The higher cylinder pressure results in an increase in power from the same amount of fuel, thereby increasing the combustion efficiency of the engine [8]. Pre-ignition within the cylinder is prevented by cooling the cylinders with air prior to combustion. The development of a unique hydrogen gas cycle and injection strategy has eradicated the problem of misfiring and is implemented by means of BMW's VANOS systems.

Under full load, the engine operates at stoichiometric conditions, with a fuel/air ratio of one, while partial loading allows for the lean combustion of hydrogen with excess air. The increased production of nitric oxides (NO_x), as a result of rich combustion, is eliminated as the engine management system automatically skips the equivalence ratios between one and two as these cause the greatest concentrations of NO_x [8].

Hydrogen fuel is stored in a double-layered, vacuum-insulated tank, as described above, and has a capacity of eleven litres of liquid hydrogen. A triple valve system ensures optimal safety at all times with the operating valve opening at a pressure of 450 kPa [8].

In addition, the insulating jacket surrounding the hydrogen tank is fitted with a further two valves, which open as soon as the pressure within the tank exceeds 500 kPa. This ensures that the tank will not rupture as the result of a build up of pressure.

The operating pressure, 300 kPa, of the fuel system is generated by the rise in temperature of the liquid hydrogen and is regulated by the tank controller. Further heating of the hydrogen fuel occurs by passing it through a heat exchanger with the engine coolant so as to ensure that it is at ambient temperature before injection [8].

Supply pipe pressure is reduced to 120 kPa by the engine management system by means of a control valve so as to ensure optimal fuel pressure under varying driving conditions [8].

Further safety features include the automatic closing of the supply valves in the event of a leak in one of the pre-flow pipes. This is achieved by a constant pressure measurement sensor within the fuel line which actuates the isolation once the pressure drops below 40 kPa [8]. Additional hydrogen sensors, fitted in the tank and around the tank coupling, also detect any hydrogen leaks and relay this information by means of telemetry to the driver.

The results of these technological advances, is a car capable of matching the performance of conventional cars with a reduction in the generation of undesired emissions. However, of even greater importance, is the fact that there now exists a means to counter the argument that a change to hydrogen power entails a reduction in the dynamic performance of a vehicle, thus further enhancing the possibility of a hydrogen future.

3.2.2 Ford Hydrogen

The development of a hydrogen engine is not unique to continental Europe, as is evidenced by the research underway at the Ford Motor Company in the United States of America.

Initially, a 2.3 litre, in-line four cylinder engine was developed for use in Ford’s Model U and Hydrogen Hybrid Research vehicles [10]. This was succeeded by the production of a supercharged 6.8 litre V10 powerplant, capable of 169 kW which is used in the Ford F-350 pickup.

Fuel is stored in a carbon fibre reinforced tank capable of sustaining a five-storey drop and, according to Ford, rifle fire [10]. At 34.5 MPa, the tank has a capacity of 360 litres, the equivalent of approximately 30 litres of petrol, and allows the F-350 a somewhat worrying fuel range of 160 kilometres, which is 320 kilometres short of the consumer expectation. Ford believes that the situation may be improved by the development of a new 69 MPa tank, thus doubling the range [10].

The fuel efficiency of Ford’s hydrogen-powered engines is claimed to be 25% better than that of their equivalent petroleum units, however, at the expense of power output. This is rectified by the introduction of a supercharger, which improves combustion and generates more power [10].

Unlike BMW, Ford believes that the development of a hydrogen-powered engine is an intermediate step in their hydrogen initiatives and will allow them the realisation of their ultimate goal; the production of a hydrogen fuel cell vehicle.

3.2.3 Hydrogen Rotary Engines

- **Introduction**

The rotary or Wankel engine, by nature of its operation, is particularly suited to the use of hydrogen as a fuel.

Unlike the reciprocating piston engine, the rotary engine has individual intake and combustion chambers, which diminishes the backfiring and pre-ignition problems encountered when using hydrogen in a conventional engine [11]. The air and hydrogen mixture is drawn into the engine as the rotor passes through the top of its cycle and is displaced to the lower right chamber where it is compressed and eventually ignited. The fact that induction and detonation occur at different points in the engine results in less complications in the combustion process [11].

Also, since the intake/exhaust cycle of a rotary engine is 50% longer than that of a reciprocating engine, the extra time allows for the possibility of injecting hydrogen into the engine after the air intake process [12]. This would eliminate pre-ignition of the fuel/air mixture as it enters through the inlet valve owing to the absence of hydrogen.

- **Mazda Hydrogen Rotaries**

Mazda, the world's only rotary-engine producer, has been experimenting with the use of hydrogen in their Wankel engines for the past decade at least. This has seen the production of the vehicles such as the hydrogen-powered Miata, the HRX versions 1 and 2, the Cappello cargo van and finally the RX-8 [13].

The Miata has a power output of 82.5 kW as compared to the petrol model's 90 kW and is fuelled from a metal hydride tank located in the boot [12].

A fleet of hydrogen-powered Cappello cargo vans, on loan to the Hirohata Steel Mill, were driven for 32 000 km on public roads and made use of tanks containing metal hydride, which release hydrogen when subjected to heat [14].

The culmination of Mazda's efforts has been the development of the RX-8 which is powered by their hydrogen-fuelled rotary "*RENESIS*" engine.

- **RX-8 RENESIS**

The RENESIS rotary engine in the RX-8, Figure 3.5 below, develops 81 kW at 7200 rpm when fuelled on hydrogen as contrasted by the 154 kW obtained from the use of conventional petroleum. Its maximum torque rating is 120 Nm at 5000 rpm as opposed to the 222 Nm produced by the petrol equivalent [13].

Figure 3.5: Mazda's Hydrogen-powered RX-8 [15]

The engine incorporates an electronically-controlled injection system where the hydrogen is injected in its gaseous state. Air is drawn in from the engine's side ports during the induction stroke and hydrogen is injected directly into the intake chamber by means of two hydrogen injectors in each of the twin rotor housings [13].

Separate induction and combustion chambers, as discussed previously, result in a lower temperature within the induction chamber, thereby allowing for the installation of the hydrogen injectors and their rubber seals. This would prove impossible in a reciprocating piston engine as the high temperatures would result in seal failure [13].

As hydrogen has an extremely low density when compared to petrol, a far greater volume is required in the combustion chamber, which necessitates the use of two injectors per chamber. This would be cumbersome when applied to the reciprocating engine as structural constraints prevent the mounting of injectors directly into the combustion chamber. This, however, is not the case with the rotary engine as there is adequate space for both injectors [13].

The fact that the output shaft of a rotary engine rotates by 270° per cycle as opposed to the 180° of a conventional engine facilitates a more vigorous intake flow and, hence, better mixing of the hydrogen/air intake charge. This results in a more uniform combustion mixture, which is crucial to the efficient combustion of hydrogen [13].

The RX-8 is equipped with both a petrol and hydrogen tank and comprises a dual-fuel system capable of operating on both fuels. Extensive road testing is currently underway and initial results indicate hydrogen reliability and operability on par with the petrol model [13].

Further developments in Mazda’s hydrogen research include the introduction of an electric motor-assisted turbocharger to the RENESIS engine in an attempt to increase the combustion efficiency of hydrogen and the regeneration of energy from the car’s exhaust [13].

3.3 Hydrogen Generation

3.3.1 Steam Reformation

Steam reformation may be defined as the process whereby a single-bonded hydrocarbon or alcohol is reacted with steam reaching 1100°C in the presence of a catalyst to produce hydrogen and carbon dioxide [16].

The steam reforming process is characterized by a strongly endothermic reaction, which yields hydrogen and carbon monoxide according to equation (3.1) below. Thermodynamically, the process is favoured at temperatures exceeding 600°C while the use of a catalyst allows a high yield of hydrogen at temperatures below 1000°C [17].

$$C_mH_n + mH_2O = mCO + \left(\frac{n}{2} + m\right)H_2 \tag{3.1}$$

This production of hydrogen is further enhanced by the “water gas shift reaction” which oxidises carbon monoxide into carbon dioxide as illustrated by equation (3.2) [17].

$$CO + H_2O = CO_2 + H_2 \tag{3.2}$$

In the case of alcohol reformation, usually methanol, equation (3.1) would be modified slightly to equation (3.3). The process begins with the vapourisation of the water and methanol by adding heat. This mixture is then passed through a chamber containing a catalyst. Upon reaching the catalyst, the methanol molecules decompose into hydrogen and carbon monoxide [17].

$$CH_3OH = 2H_2 + CO \tag{3.3}$$

The oxidation reaction illustrated in equation (3.2) above remains the same once the alcohol has been reformed.

Steam reformation is a relatively efficient and inexpensive process and can be even more efficient with the collection of waste heat, known as cogeneration. However, the reformation process does produce carbon dioxide, a greenhouse gas, as a byproduct of the reaction [17]. These levels of carbon dioxide generated, even though less than those resulting from the combustion of fossil fuels in an internal combustion engine, is the greatest shortcoming in the use of steam reformation as a means of producing hydrogen.

3.3.2 Electrolysis

Electrolysis, as shown in Figure 3.6, may be defined as the process involving the decomposition of an electrolytic solution, in this instance water, by means of an electric current to produce hydrogen and oxygen gas.

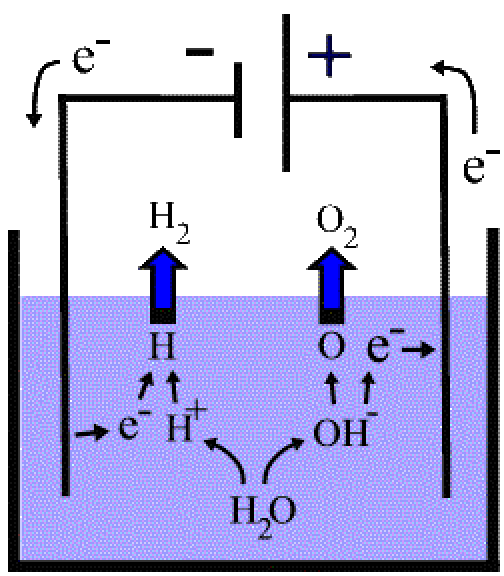

Figure 3.6: Electrolysis of Water [18]

This chemical reaction may be described as follows [19]:

$$2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)} \tag{3.4}$$

At the cathode, the negatively charged electrode, water molecules are dissociated into positively charged hydrogen ions and negatively charged hydroxide ions. The hydrogen ion is, thus, in a position to pick up an electron from the cathode and forms conventional hydrogen gas, which bubbles to the surface [18]. The overall chemical equation for representing this process is given in equation (3.5) below [19].

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{3.5}$$

The hydroxide ion is then attracted to the anode, the positively charged electrode, where it removes an electron from the anode and recombines with three other hydroxide ions to form one oxygen molecule and two water molecules. The resultant oxygen, as was the case with the hydrogen, bubbles to the surface. This process can be described according to equation (3.6) [19]:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{3.6}$$

While the use of electrolysis for hydrogen generation results in no harmful byproducts, the high level of inefficiency inherent in the process of converting water to hydrogen and oxygen is its biggest drawback. However, new technologies in electrolytic processes, such as pulsed electrical signals, may increase the efficiency of the electrolysis process to such an extent that it becomes economically viable.

3.4 Paper 1: Performance Characteristics of Hydrogen Fuelled Engine with the Direct Injection and Spark Ignition System [20]

3.4.1 Introduction

This study involved the optimisation of certain performance characteristics of a 0.433 litre direct injection, spark ignition engine fuelled on hydrogen. Various engine operating parameters, such as injector hole configuration, injection timing and spark timing were varied for both petroleum and hydrogen fuelling so as to facilitate a comparison between the two. Engine torque for both fuels was also determined.

The effect of injector hole configuration was determined by conducting tests with four variants of injector nozzles. Similarly the relationship between both injection timing and spark timing respectively and torque was investigated by running the engine at different settings.

3.4.2 Results and Discussion

The results for injector hole configuration indicated that the variation in torque across the four types of nozzles was extremely small [20]. This would imply that the engine performance was independent of injector hole configuration.

However, another crucial factor in determining an optimal injector configuration, other than output torque, was the driveability of the engine. This could be characterised by the degree of cyclic variation in indicated mean effective pressure (imep). The coefficient of variation, being a measure of imep variation, was found to be lowest for the full open injector type as compared to the other three nozzles [20].

Under stoichiometric conditions and at an engine speed of 1600 rpm, the maximum torque was seen to occur at an injection timing of 12º before top dead centre (BTDC). Retardation of the injection timing beyond this point resulted in an exponential decrease in torque which was attributed to a reduction in injection quantity due to the compression effect of the piston [20].

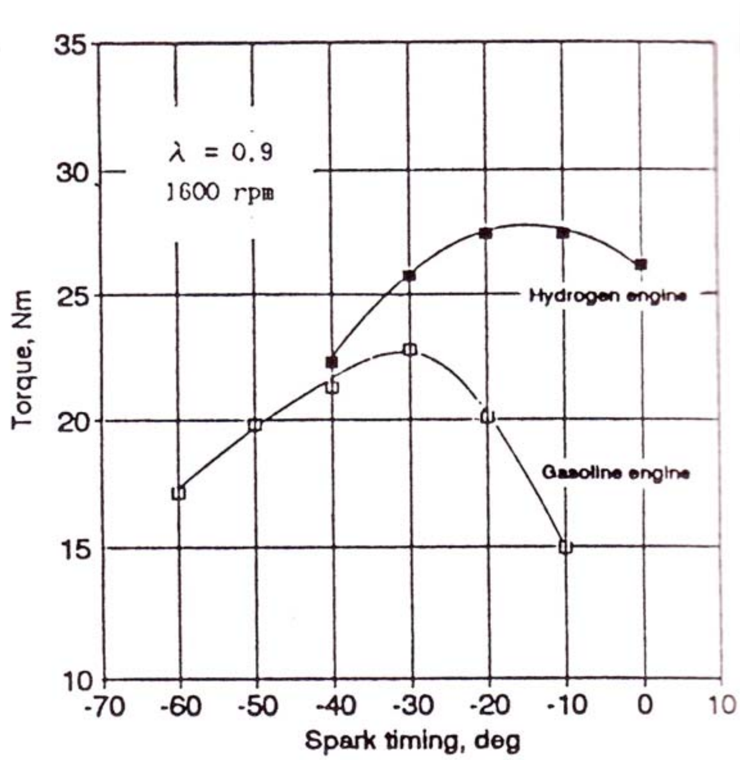

Figure 3.7: Maximum Brake Torque vs. Spark Timing [20]

Figure 3.7 above illustrates the relationship between Maximum Brake Torque (MBT) and spark timing. It can be seen that the MBT for hydrogen is greater than that of petrol across the timing range. However, maximum torque occurs at a spark timing of 30º BTDC for petrol as opposed to the retarded value of 15º BTDC for hydrogen.

Output torque was found to be higher throughout the equivalence ratio domain from the use of hydrogen at 1600 rpm. It was also seen that the hydrogen torque band extended beyond that of petroleum into the lean combustion region [20]. However, maximum torque occurred at an equivalence ratio of approximately 0.9 for both fuels.

From figure 3.8 below, it can be seen that the torque produced by the engine is greater with hydrogen fuelling than from the use of conventional petroleum. This increase in torque is more pronounced at lower engine speeds.

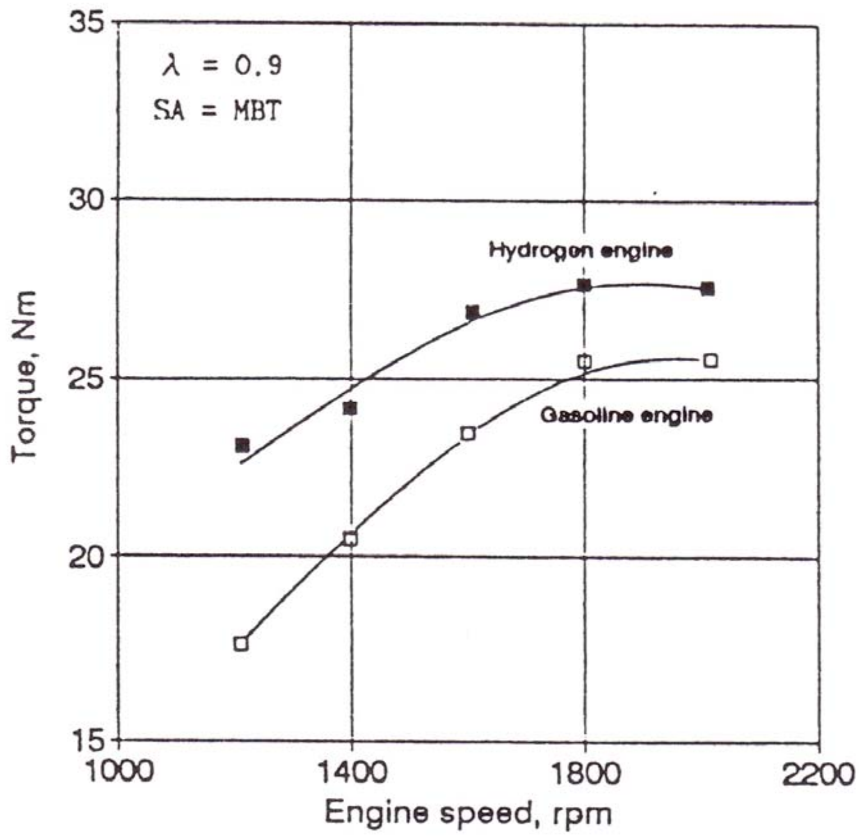

Figure 3.8: Torque vs. Engine Speed [20]

3.4.3 Conclusions

From the results obtained above, it was concluded that [20]:

- The full-open type of injector hole configuration was most suitable to the use of hydrogen as it resulted in the best driveability.

- An injection timing of 12º before top dead centre was optimal which would allow sufficient mixing of the fuel and air.

- The best spark timing for maximum brake torque was 15 º BTDC.

- The range of equivalence ratio for adequate torque delivery was greater from the use of hydrogen.

- An increase in torque of approximately 20% with hydrogen fuelling was obtained.

3.5 Paper 2: Hydrogen Internal Combustion Engine Boosting Performance and NO_X Study [21]

3.5.1 Introduction

The experimental investigation undertaken entailed the analysis of the performance and nitrogen oxide emissions of a 2.3 litre Duratec engine fuelled on hydrogen with a compression ratio of 12.2:1.

Various improvements, such as piston material, valve seat geometry and piston ring design were implemented in an attempt to boost engine power and torque while maintaining low levels of NO_x.

3.5.2 Results and Discussion

The emissions from the use of hydrogen were found to be inherently low. NO_x emissions were seen to be lowest at an equivalence ratio of 0.5 after which they increased as a function of equivalence ratio. The highest values of NO_x occurred at an equivalence ratio of 0.8.

With the engine throttled at the world-wide-mapping point (WWMP), at an engine speed of 1500 rpm and a brake mean effective pressure (BMEP) of 2.62 bar, the NO_x emissions were determined as being 90 parts per million (ppm). Unthrottled conditions resulted in 3-4 ppm of NO_x at an equivalence ratio of 0.23.

Unburnt hydrogen emissions peaked at approximately 7000 ppm at an equivalence ratio of 0.8 and were lowest at a value of 0.5 for equivalence ratio at 2000 ppm.

Carbon dioxide and carbon monoxide concentrations averaged at approximately 10 ppm and 5 ppm respectively across the BMEP range. Total unburnt hydrocarbons were approximated at 5 parts per million throughout the BMEP domain.

3.5.3 Conclusions

The following conclusions could be drawn:

- Carbon based emissions remained almost zero even under boosted conditions.
- Exhaust gas recirculation and a three-way catalytic converter provide an effective means for reducing NO_x emissions.
- An EGR strategy can produce between 23% and 28% more torque than a lean-burn strategy with NO_x emissions below 5 parts per million.

3.6 Paper 3: Performance of a Spark-Ignition Engine Fuelled with Hydrogen using a High-Pressure Injector [22]

3.6.1 Introduction

The focus of this research was to present and discuss the results obtained from the use of a high pressure injector in the supply of hydrogen to a conventional spark ignition engine.

Baseline tests were conducted on standard petrol to form a basis of comparison for the performance characteristics of the hydrogen fuelled engine. A compression ratio of 8:1 was chosen and the engine was operated over a range of throttle settings at engines speeds of 1200, 1500 and 2000 rpm.

Hydrogen tests were performed at a compression ratio of 12:1 and NO_x emissions were recorded at 1500 rpm for various equivalence ratios.

3.6.2 Results and Discussion

NO_x results for hydrogen were seen to decrease as the relative air/fuel ratio increased as indicated in Figure 3.9 below. Maximum NO_x concentrations were found to occur at a relative A/F ratio of 1.3 after which dropped off abruptly until a value of 1.8.

NO_x emissions were extremely small for relative A/F ratios greater than 1.8. This was due to the fact that at conditions slightly leaner than stoichiometric, surplus air at a similar flame temperature to that at stoichiometric conditions aids the production of NO_x.

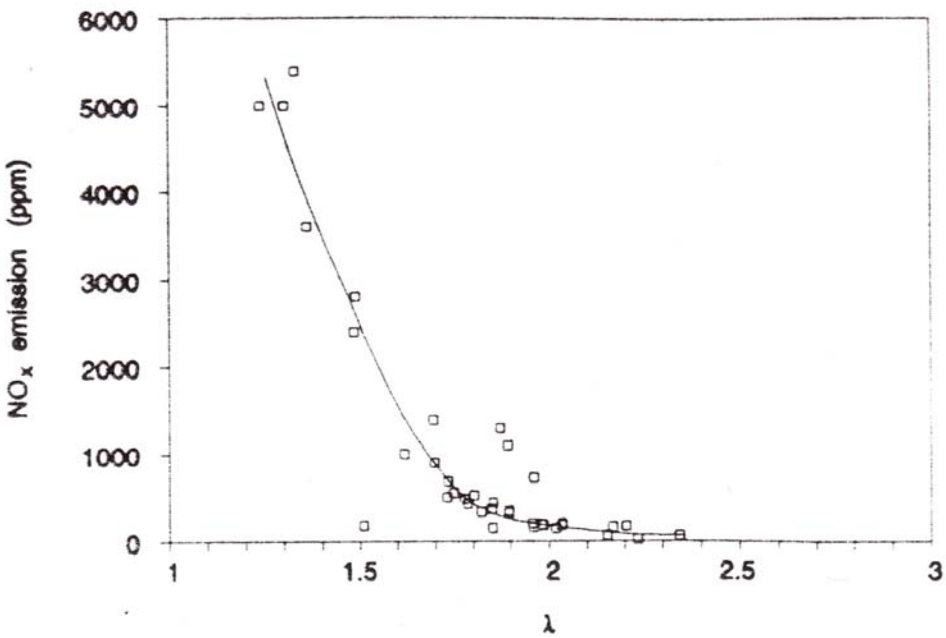

Figure 3.9: NO_x emissions from Hydrogen testing vs. Relative Equivalence Ratio λ [22]

3.6.3 Conclusions

It was concluded that:

- The concentration of NO_x in the exhaust was very low for operation of the hydrogen engine leaner than λ = 1.8.
- Operation closer to stoichiometric increased NO_x emissions to similar levels as those resulting from petroleum fuelling.

3.7 Nitrogen Oxide (NO_x) Formation [23]

Nitrogen oxides, or NO_x, are byproducts of the combustion process and are generated within the combustion chamber during combustion as a result of the reaction between atomic oxygen and nitrogen [23].

The reactions involved in the formation of NO_x are extremely dependent on temperature thus, the NO_x emissions from an engine are found to be proportional to the engine load. Therefore, NO_x concentrations are expected to be minimal during start-up and warm-up periods.

The three mechanisms involved in the formation of NO_x are the thermal or Zeldovich mechanism, the Fenimore or prompt mechanism and the N_2O intermediate mechanism. The Zeldovich mechanism, in which NO is formed in the high temperature burnt gases left behind by the flame front, is the most significant when dealing with internal combustion engines and is, therefore, used.

The Zeldovich mechanism comprises three chemical equations to form the extended reaction, namely; [23]

$$O + N_2 \leftrightarrow NO + N \qquad (3.7)$$

$$N + O_2 \leftrightarrow NO + O \qquad (3.8)$$

$$N + OH \leftrightarrow NO + H \qquad (3.9)$$

Equation 3.7 is the reaction entailing the dissociation of nitrogen and was initiated by an oxygen atom. The reaction was endothermic, thus making it the controlling equation. Hence, the dependence on oxygen concentration in NO_x formation was established.

Figure 3.10 illustrates the relationship between NO_x concentration and equivalence ratio. The NO_x concentration is seen to be maximum with fuel mixtures slightly leaner than stoichiometric.

As mentioned previously, higher temperatures aid NO_x formation and while the gas temperatures were greater for richer mixtures, the low excess oxygen in these mixtures hindered their generation, as they could not attach to the nitrogen atoms to form nitric oxide. The combined yet counterbalancing influence of temperature and oxygen content resulted in maximum NO_x concentration occurring at equivalence ratios slightly less than unity.

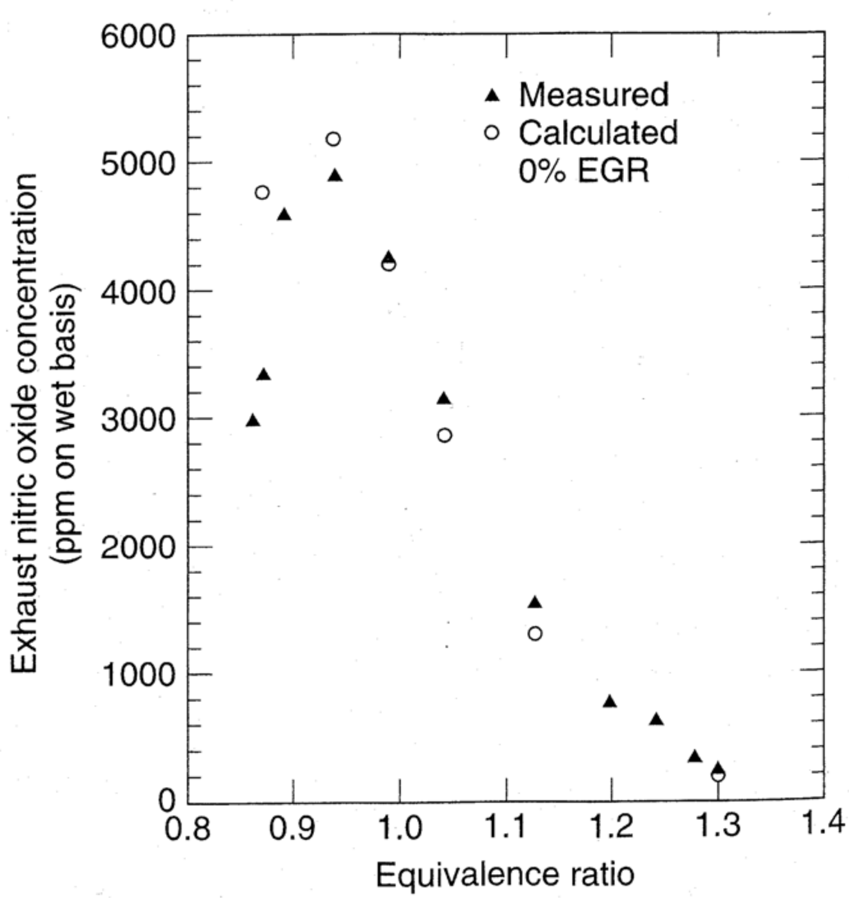

Figure 3.10: NO_x Concentration as a function of Equivalence Ratio [23]