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Hydrogen IC Engine for Heavy Duty Vehicles

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A dissertation submitted in partial fulfillment of the degree of BAI (Mechanical and Manufacturing Engineering)

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Abstract

Research papers on using hydrogen as an alternative fuel to traditionally used carbon-based fossil fuels for vehicular engines date back to the 1930s. Various companies, universities and research institutes have been researching and publishing papers on the use of hydrogen as a fuel in vehicles either in fuel cells or combusting hydrogen in the combustion chamber of an engine or using it as a bi-fuel operation along with gasoline or diesel for increased efficiency. Many papers suggest changing a few parts and characteristics in a diesel or gasoline engine in order to combust hydrogen in the engine to generate power and torque for the movement of a vehicle like spark plugs, air-fuel mixture injectors, etc. The how and what of using air boosting with the hydrogen engine for a better power delivery or efficiency have been greatly researched upon by many such educational institutions.

This paper focuses on the air boosting technology on hydrogen engines. Topics discussed in this review argue if air boosting is required in the engines, and if yes, what kind of air boosting and what are the parameters associated with using air-boosting in a hydrogen engine. The paper also reviews how NOx emissions in hydrogen engines can be reduced effectively at high engine speeds.

Upon doing extensive literature reviews on hydrogen combustion engines and their 3 different air boosting systems, it was found that EGR at high engine speeds was more efficient in curbing NOx emissions while a loss in torque and brake thermal efficiency (BTE) was a penalty for it. Superchargers when used in hydrogen engines certainly provided more power even at low speeds but with high NOx emissions. Superchargers can provide performance comparable to gasoline engines but additional equipment is required for such an operation. Turbochargers come out as a better boosting system to be used in a hydrogen engine since it is effective in decreasing NOx emissions along with increased boosted power generated by the engine. For more effective analysis and comparison, more research is needed into the mixture injection systems' effects along with air boosting systems on similar engines such that the basic parameters of analysis remain the same while the changing constraints can be controlled.

Contents

1 Introduction

Global warming has been an increased source of danger for the planet in recent times. The use of carbon based fossil fuels in vehicles for combustion results in pollutant gasses like carbon dioxide (CO_2), carbon monoxide(CO), methane(CH_4), and nitrous oxide (N_2O) [2]. The gasses in excessive amounts trap the heat of the sun in the atmosphere of the earth which in turn increases the temperature of the planet. In recent findings, by 2030, there will likely be 55 gigatons of emissions discharged into the atmosphere [1]. As of 2022, the global emissions of CO_2 has increased to 34 billion tonnes a year as compared to 22 billion tonnes in 1990 [3, 4].

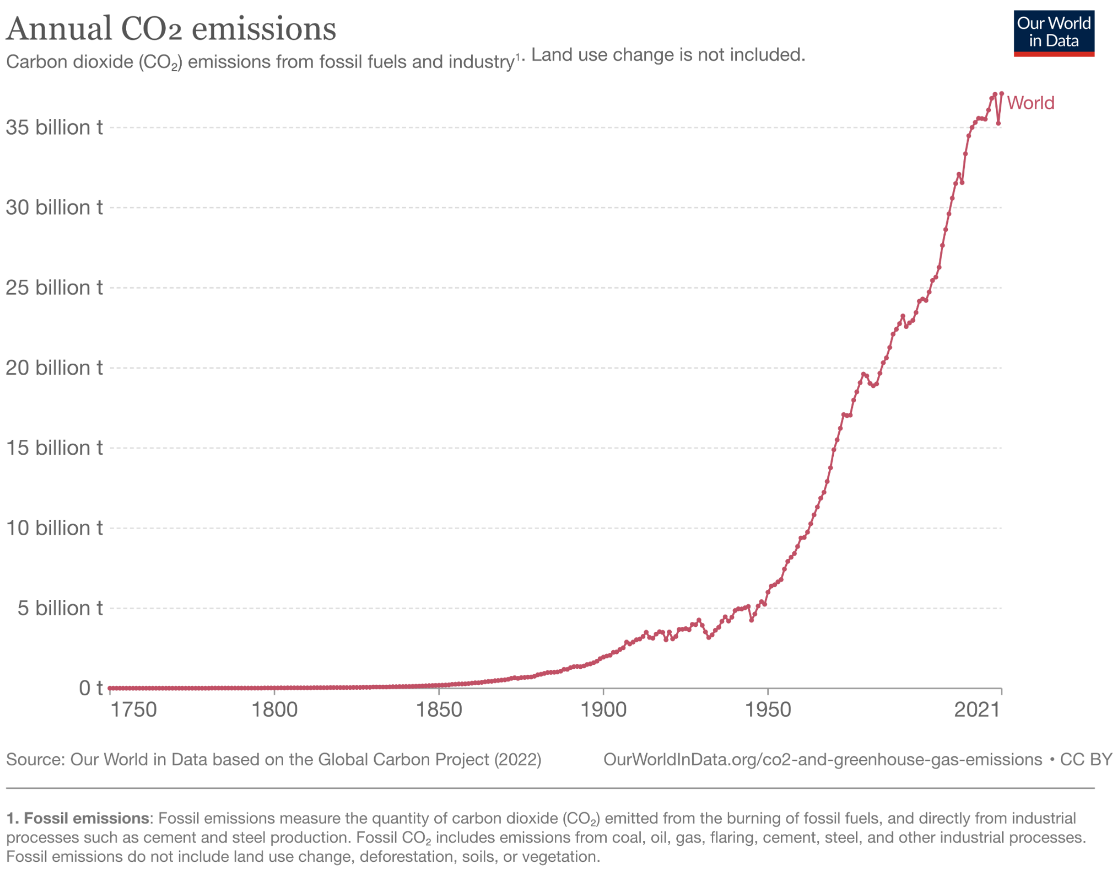


Figure 1. Chart showing the increase in annual CO_2 emissions as compared to the past till 2022. [4]

In such circumstances, the requirement of clean and renewable fuels for vehicular use has increased.

One such alternative is the use of electric vehicles (EV), that is, a vehicle with a battery holding some charge which in turn helps power one to two or more motors in the vehicle for propulsion. However, since the objective of further research for safer alternatives is for a better and sustainable environment for the future generations, usage of EVs does not serve the purpose. Although there are many advantages to using EVs, researchers suggest that production of an electric vehicle takes twice as much the energy required to produce a vehicle using internal combustion engines (ICE) [5, 6], mainly due to the battery production. The process of mining and processing minerals required for battery production, and the manufacture of the battery for an EV requires about 350-650 kWh of energy, which in turn causes the release of 150-200 kg of CO_2 per kWh [6]. Another drawback comes to be the consumption of fossil fuels to generate the large amount of electricity required to charge the EVs, as in the case of Germany, that is, more than half of the electricity generated comes from burning fossil fuels [7, 8]. Even though EVs do not cause the pollution of the air with the emission of harmful gasses like nitrous oxide or carbon dioxide, the combustion of carbon based fossil fuels would indirectly affect the environment, leaving it unsafe for future generations [9]. Although EVs seem good for the environment, repeated long distance travels without frequent charging does not seem realistic. In lieu of this logic, EVs application does not suit heavy duty vehicles that require long distance travels for deliveries and transportation while racking heavy loads.

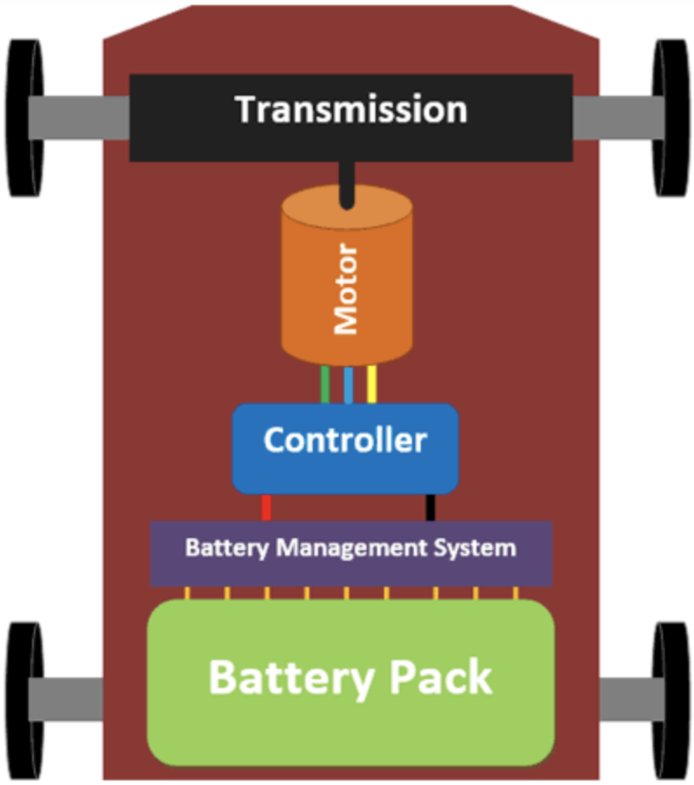


Figure 2. Basic schematic of an electric vehicle (EV) [10].

Researchers have been targeting hydrogen as a viable alternative fuel for the propulsion of a vehicle. Hydrogen can be used in two ways in a vehicle– i. Hydrogen Fuel Cell (FC) and ii. Hydrogen Internal Combustion Engine (HICE).

However, using hydrogen as a fuel comes with its own challenges. For example, Hydrogen storage is thought to be difficult. Hydrogen that has been liquefied needs less storage space than hydrogen that has been gasified, although doing so results in energy loss and consumption. While materials suited for the tanks and infrastructure for transporting the hydrogen still seek scientific and financial improvement, the storage of gaseous hydrogen requires specially built storage tanks that can sustain high pressure [11]. Materials that can enable storage of hydrogen should be lightweight, low-cost, recyclable and have excellent kinetics of adsorption and desorption [12].

Hydrogen fuel cell vehicles (FCV) use the concept of generating electricity using electrolysis with an anode, a cathode and an electrolyte. Since FC technology is expensive, it is more predominantly being applied for city buses [13]. The logic behind being the buses refueling at the same place, so only one hydrogen filling spot is required rather than spending a lot of money for fueling stations across the city [13]. The fuel cell's basic operation is as follows: air or pure oxygen is fed into the cathode side of the fuel cell while fuel (pure hydrogen) is injected into the anode compartment. As the gas tries to get through the electrolyte membrane Proton Exchange Membrane (PEM) on the anode side of the cell, electrons are divided. The membrane serves as a filter, preventing the passage of electrons and allowing only the passage of hydrogen ions (protons). The hydrogen ions that made it past the membrane in the cathode compartment interact with the oxygen atoms from the air supply to create H_2O as a byproduct, along with heat [15]. Heavy-duty engines release pollutants into the environment, but they are not going to be phased out anytime soon as alternatives like large-scale fuel cell manufacture are still challenging and expensive to implement [17].

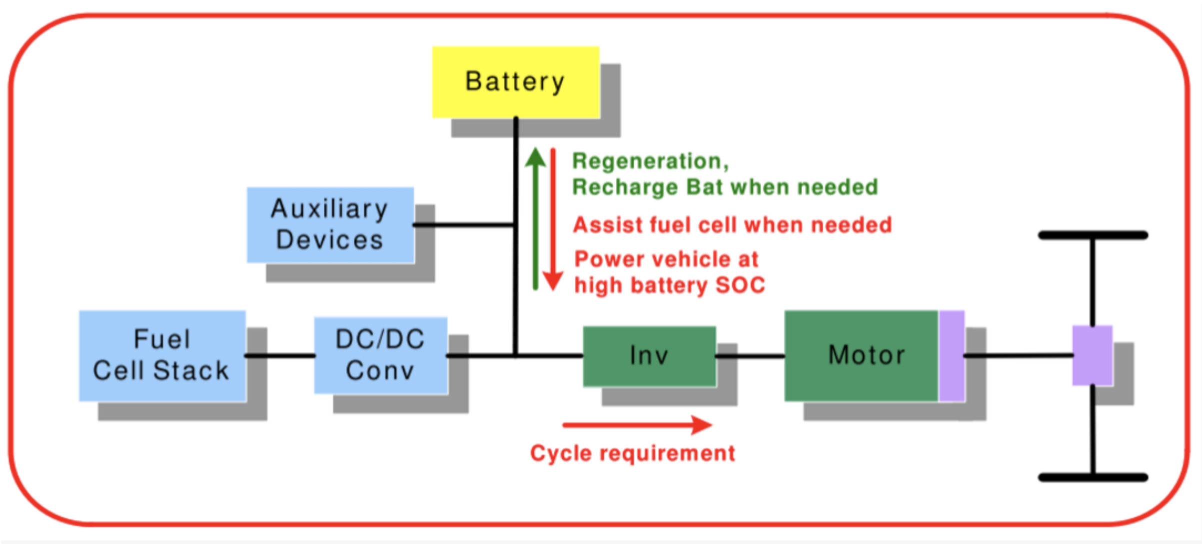


Figure 3. Basic configuration of a Hydrogen Fuel Cell Vehicle [16].

Using hydrogen as a fuel for combustion in an internal combustion (IC) engine has its own advantages. Due to its high energy density by mass, that is, high energy delivery on combustion of a specific mass of fuel, hydrogen serves a viable clean fuel for IC engines [13]. The by-products of said combustion are water, NOx emission (nitrous oxides) from the air supplied into the combustion chamber of the engine, and minute carbon emissions due to the engine oil. NOx emissions can be dealt with using catalysts in the exhaust system of the vehicle, or by sufficient air boosting like exhaust gas recirculation (EGR), turbocharging, and supercharging. A lean mixture causes a low flame temperature when running the engine. Due to the overall amount of fuel burned, this results in reduced heat transmission to the walls and allows for greater fuel efficiency. Also, the high degree of flammability (the proportion of combustible gas to air that makes up a flammable combination) of hydrogen permits the operation of extremely efficient engines, which reduces NOx emissions and improves brake thermal efficiency [26]. It allows the engine to use quality regulation to manage the power output by controlling the fuel flow rate and keeping the air unthrottled [21]. Since hydrogen as a fuel when burnt, releases negligible carbon based emissions (due to engine oil) [31], it makes a good option for alternative fuels. Hydrogen is regarded as a suitable combustion fuel due to its rapid flame speed, low required ignition energy, and high adiabatic temperature [40].

However, using hydrogen in a bi-fuel operation along with diesel in a compression ignition engine is highly researched upon [36, 37] due to its effects on reducing emissions by a large factor.

Compared to coal, gasoline, and methane, hydrogen has a heating value that is 4, 3 (nearly), and 2.4 times higher, respectively [18]. Below is a table[19] that compares the characteristics of gasoline and diesel to hydrogen for fuels for IC engines.

Table 1. Comparison of different fuels with hydrogen [19].

Properties	Hydrogen	Gasoline	Diesel
Carbohydrate content (mass %)	0	84	86
Molecular mass	2.015	110	170
A/F Stoichiometric ratio	34.3	14.6	17
Temperature of Ignition (K)	858	530	-
Temperature of adiabatic flame (K)	2384	2270	2300
293 K (cm/s) flame speed	237	41.5	-
Flammability Limits (vol% in air)	4.1 - 75	1.5 - 7.6	0.6 - 5.5
Quenching the gap (cm)	0.06	0.2	-
Lower heating value per kilogram (MJ/kg)	120	44	-
Diffusion coefficient (cm^2/s) under stoichiometric conditions	0.61	0.05	-

Clearly, using hydrogen as a fuel for combustion in IC engines is more sustainable for the environment. Because of its higher ignition temperature, hydrogen is more suited for a spark ignition (SI) IC engine than a compressed ignition (CI) IC engine [20]. In comparison to the demonstrated efficiency of a spark ignition hydrogen fuelled IC engine [32] and a compression ignition hydrogen fuelled IC engine [33], it was revealed that an SI engine has an increased engine efficiency of 52% to the latter's 49% [34], because the higher auto-ignition temperature is easily reached with the help of a spark than with compression [31].

This paper aims to review the current knowledge of engine air boosting technology in case of hydrogen IC engines (HICE), whether air boosting is required for a better efficiency in power and performance. If yes, the kind of boosting required for the desired output will also be determined. The paper will also argue on reducing NOx emissions in each of the boosting conditions. In this paper, we will mainly be dealing with spark ignition (SI) hydrogen fuelled IC engines.

The following chapter will explain more about HICEs– what needs to be changed in an engine in order for it to run on hydrogen directly. Consequent chapters will include information on the challenges of hydrogen combustion in a HICE, detailed review of air boosting systems in a HICE (Exhaust Gas Recirculation, Supercharger boosting, and Turbo boosting) and arguments on reducing NOx emissions in each system.

2 Hydrogen Fuelled Internal Combustion Engine

2.1 Air-Fuel Mixture Injection Systems

The method of using the kind of injectors, their timing and the strategies they use deeply influence the torque and efficiency of an engine. There are two types of injection methods used in the case of hydrogen combustion engines:

1. Port Fuel Injection (PFI) - external mixture formation using a programmable manifold [39, 48, 49].

2. Direct Injection (DI) - formation of mixture inside the combustion chamber [50, 51].

3. External mixture formulation through the use of a gas carburetor and water injection, at times used with EGR [52].

4. External mixture formation with "parallel induction," or some other method of postponing the entry of hydrogen, such as a fuel line shut off by a separate valve above the intake valve that only opens when the intake valve has raised sufficiently [53].

5. Using a carburetor for the formation of mixture externally [54].

The four-stroke cycle, also known as the Otto cycle, is a fundamental mechanism governing the operation of internal combustion engines. It begins with the intake stroke, in which the piston moves downward and draws a mixture of fuel and air through the intake valve. This mixture is then compressed during the compression stroke as the piston rises, increasing the mixture's temperature and pressure. The combustion, or power, stroke is the critical phase in which the spark plug ignites the compressed mixture, causing a rapid expansion of gasses that forcefully pushes the piston downward and generates power. During the exhaust stroke, the piston expels the consumed gasses from the combustion chamber via the exhaust valve. This continuous cycle of intake, compression, combustion, and exhaust strokes allows the engine to generate power and propel a variety of applications. On the other hand, in diesel engines, the air-fuel mixture is ignited when it is compressed to high pressures in the engine due to low combustion temperature of diesel as a fuel, thereby negating the use of a spark plug.

PFI (Figure 4, left) is when fuel is added into the mixture before the intake valve during the intake stroke, while DI (Figure 4, right) is when the fuel is introduced into the intake manifold directly, preferably during the later stage of the compression stroke [34]. This however is used with high pressure fuel charge to counteract the compression during the compression stroke unlike during PFI [34, 46, 60]. PFI systems can widely be used during lower engine speeds to ensure higher efficiency and lower NOx emissions [46, 55, 56] due to more mixing time of mixture. On the contrary, while DI systems are used for higher engine speeds, delaying the introduction of hydrogen fuel into the intake manifold (as mentioned above) creates opportunity for lower NOx emissions [46, 57, 58, 59, 60].

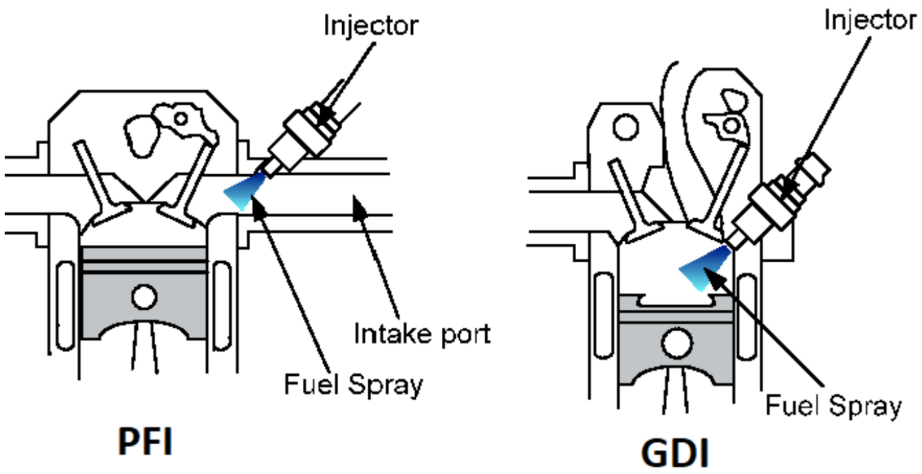


Figure 4. Basic schematic of PFI vs DI (or GDI - Gasoline DI) [61].

Compression ratio of an engine is the ratio of the largest volume of a cylinder to its smallest volume, that is, a ratio between the volume of the cylinder when the piston is at its lowest point to its highest point in a combustion cycle. The greater the compression ratio, the more compressed the air-fuel mixture. This in turn brings the piston closer to the center of combustion. The closer the piston is to the center of combustion, the greater the power transferred to the piston, implying more power being generated from combustion in the engine with better efficiency.

Back in 1998, Peschka W. [64], proposed the dependency of power delivery of a hydrogen combustion engine on the quality of air-fuel mixture used.

Hydrogen internal combustion engines gain a great deal from DI strategies, which mitigate the drawbacks of PFI systems, including air displacement effects, clanging, backfiring, and low power density [65].

Consequently, a different method to introduce the air-fuel mixture of hydrogen fuel into the combustion chamber of an internal combustion engine was introduced, dual injection method (Figure 5). This method involves the integration of DI and PFI methods, effectively using their strengths at times of need. When the engine is at its high speed PFI is required to be executed while DI is more required when the engine is running at low speeds (more explained later).

Yang et al. [67] deduced after experimenting on the geometrical structure parameters of a modified Jaling JH600 single-cylinder HICE with four valves in a 3D representation. It had a compression ratio of 9.7:1, that for all engine velocities and gear ratios, indicated power and indicated thermal efficiency are at their highest when dual injection is utilized, and their lowest when single injection is used. When the engine speed is 1000r/min and the equivalent ratio is 0.67, the indicated power and indicated thermal efficiency increase by 26.9% and 2.22% with symmetric dual injection and by 28.6% and 3.01% with dispersed dual injection compared to single pipe injection [67]. They [67] concluded that by utilizing dispersed dual injection, both power output and fuel economy can be greatly enhanced. However, NOx emissions rise using dual injection method.

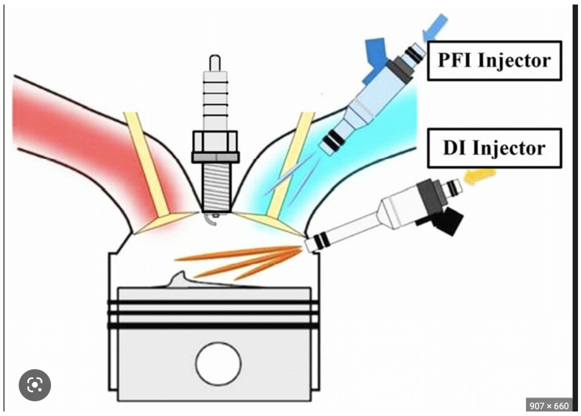


Figure 5. Basic schematic of a dual injection system [74].

2.2 Challenges

While there are many advantages of using hydrogen as a fuel for combustion in an internal combustion engine, there are quite troublesome challenges that come along with them. With hydrogen-fueled ICEs, the issue of anomalous combustion has not yet been totally fixed. Modifications to the engine architecture, mixing technique, and load control are typically necessary to address this issue. In spark ignition engines, there are typically three regimes of aberrant combustion. Knock combustion, which results in spontaneous igniting in the final gas area, is the first. Pre-ignition, or uncontrolled ignition brought on by a hot area, is the second. The third is backfire, which is sometimes referred to as backflash, flashback, or induction ignition. Backfire is an early stage of pre-ignition that occurs during the suction stroke [27-30].

Due to the enormous mechanical and thermal strains brought on by the large amplitude of pressure waves during knocking combustion, the engine may be damaged. Due to the fast burning speed of the hydrogen mixture used in ICEs, knocking combustion can have particularly negative effects [31]. Researchers concluded a list of aberrations causing the occurrence of abnormal combustion. Some of these are [31, 34]:

- The exhaust valve head's hot surface
- Combustion process's hot combustion gasses
- Scalding spark plug parts
- Combustion that takes place in the space between the piston and the cylinder.
- The quenching gap (the fuel inside the combustion chamber rapidly cooling, which stops it from burning) for hydrogen mixes varies.
- Energy leftover in the ignition circuit
- Induction in the ignition cable

However, it is positive to note that along with problems came its solutions to reduce the occurrence of abnormal combustion in a hydrogen fueled IC engine. Some of these are [31 ,34]:

- Suitable, dedicated spark plug design;
- Maximum reduction in the residual charge in the ignition system
- Adjustment of the crankcase ventilation system
- Use of sodium-filled exhaust valves
- Restriction of the occurrence of hot spots by means of an appropriate course of the cooling channels in the engine head
- Hydrogen-adapted direct-injection systems
- Optimization of valve timing for increased efficiency
- Adjustment of valve timing for efficient use of hydrogen.
- Methods for injecting clean air into the combustion chamber to cool any potential hot spots before aspirating the air-fuel mixture
- The port-injected hydrogen engine can run with a stoichiometric mixture over the whole speed range thanks to optimization of the fuel injection method and variable timing phases for both the intake and exhaust valves.

2.3 Changes to be made in an IC engine for hydrogen use

In order to use an IC engine with hydrogen, several important changes need to be made. Certain changes need to be made to an ordinary internal combustion engine so as to get the desired outcome.

2.3.1 Spark Plugs

Because hydrogen fuel burns with a fast flame, cold spark plugs with low electrode temperatures should be used to prevent early combustion and flashback. The spark plug electrode should also be made of a material that prevents hydrogen oxidation [21].

2.3.2 High Temperature Points

High temperature hot spots in the combustion chamber of hydrogen-fueled engines result in anomalous combustion and a reduction in engine output. To prevent this undesirable circumstance, the combustion chamber's temperature must be lowered [22].

In order to avoid the development of hot zones in the combustion chamber, the quantity of intake and exhaust valves might be increased. To lessen heat demands around the cylinder head and the valves, more cooling water ducts might be opened [22].

2.3.3 Lubricating Oil

The fuel and lubrication system in internal combustion engines has an impact on both the characteristic values the engine produces and its service life. Certain lubricating oil qualities may deteriorate and negatively impact the system as a result of the combustion of the fuel used in the engines. Despite the fact that a specific oil is required for internal combustion engines that run on hydrogen fuel, such an oil has not yet been invented [23].

2.3.4 Changes in Material Structure

Engine material structure's ductility is decreased and its brittleness is increased in internal combustion engines that use hydrogen. This is a result of the chemical reaction between the engine surface and hydrogen fuel mixture [22]. All metals are susceptible to hydrogen embrittlement when in contact with hydrogen, as is well known. This takes place when atomic hydrogen diffuses into the material, resulting in its brittleness. The phenomenon typically becomes significant when it results in splitting [31].

2.3.5 Turbulence formation in combustion chamber

Hydrogen can burn more quickly in combustion chambers with strong turbulence inside the cylinder due to its high flame speed. Turbulence level affects the figures for combustion length and pressure [24]. With an increase in piston speed, turbulence intensity also rises. By thoroughly mixing fuel and oxygen, turbulence quickens chemical reactions. Turbulence causes a rise in flame speed that shortens the duration of combustion, which lessens the likelihood of detonation [76]. When there is too much turbulence, the flame may be put out. Turbulence increases the heat flow to the cylinder wall [76]. The maximum pressure may be reduced as a result of excessive turbulence, but the rate of pressure rise is increased, which causes the crankshaft to spring and the rest of the engine to vibrate. causing the engine to operate rough and loudly because of its high frequency [76].

2.3.6 Oil pan ventilation

The oil pan ventilation system must be taken into account while employing hydrogen in internal combustion gasoline engines. Without this device, hydrogen might build up in the engine's lubrication system [25].

The following chapter will present different types of air boosting technology that can be used for a hydrogen fuelled IC engine to improve the engine efficiency, including reducing NOx emissions and increasing power delivery efficiency. This will include Exhaust Gas Recirculation (EGR), turbocharging, supercharging.

3. Air Boosting in Hydrogen IC Engine

Air boosting is required in an internal combustion engine burning any fuel to increase the power output and regulate the emissions caused due to the combustion. There are 3 types of air boosting systems– 1. Exhaust Gas Recirculation; 2. Turbocharging; 3. Supercharging.

Quite often EGR is used with turbochargers or superchargers in order to increase the power delivery such that emissions are reduced and power is increased, thereby compensating for the power loss caused by EGR [35].

However, before we proceed, a few concepts regarding air - fuel ratio must be considered. Air-fuel equivalence ratio (λ) is often associated with air-fuel ratio comparison with the stoichiometric ratio for the nature of the burn. Stoichiometric ratio is how much air we need to burn a given amount of fuel completely leaving no oxygen or fuel behind (mass of air to mass of fuel), while fuel-air equivalence ratio(ϕ or 1/λ) is the ratio of stoichiometric air to fuel ratio to the actual air to fuel ratio in the engine. Stoichiometric ratio for hydrogen is 34:1.

Lean burn combustion means less fuel and more air to burn in the combustion chamber of IC engines, generally used for fuel efficiency in low throttle positions. For this, air-fuel ratio should be greater than the stoichiometric ratio ($\lambda>1$) and ($\phi<1$) equivalence ratio be less than 1.

On the other hand, rich burn means using more fuel and less air for peak torque and power delivery. For this, we need air-fuel ratio is less than or similar to the stoichiometric ratio ($\lambda<1$) and ($\phi>1$).

When a hydrogen internal combustion engine is run under extremely lean conditions (by employing extra air for charge dilution), the NOx emissions are naturally low [39].

High temperatures reached during the combustion process in the combustion chamber produce nitrogen oxides. Some of the air's nitrogen combines with oxygen when exposed to heat. NOx production is affected by the air-to-fuel ratio, compression ratio, engine speed, ignition timing, and thermal dilution [40, 41, 42].

We will be discussing each of the boosting technologies and their effects on NOx emissions and efficiency in the hydrogen IC engine.

3.1 Exhaust Gas Recirculation (EGR)

EGR is the technique of redirecting a portion of exhaust gas from the exhaust manifold into the intake manifold such that the air going through the intake valve of the engine before combustion is diluted and has some exhaust gasses in the mix to reduce NOx emissions using an EGR valve to guide the redirection of the exhaust gasses. Often an EGR cooler is also required to cool the air after it is released from the engine and before it is mixed with the intake air. When the oxygen content in the intake air is diluted due to the mixing of exhaust gasses, the temperature decreases, thereby decreasing NOx production.

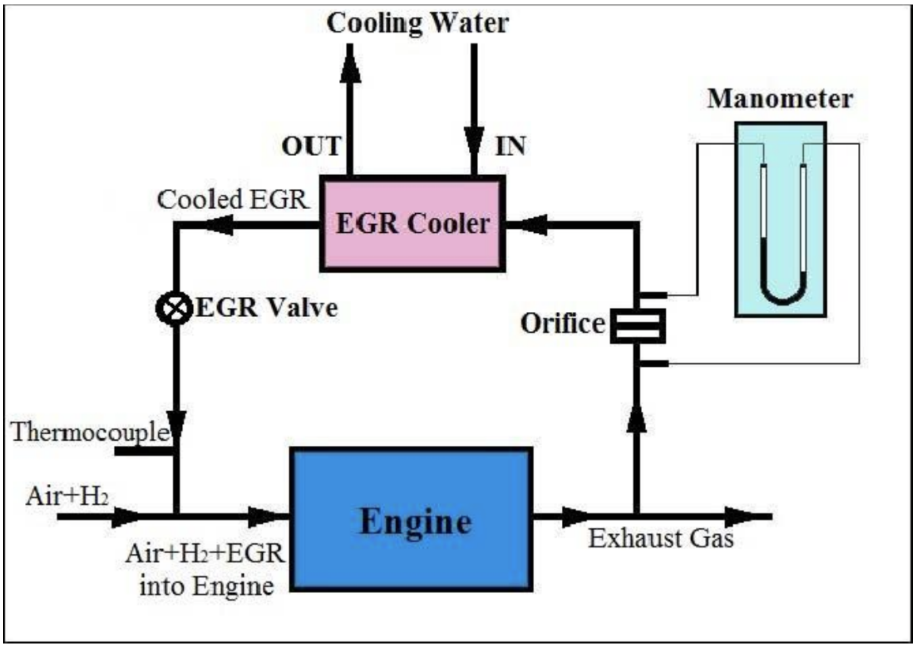


Figure 6. EGR schematic with EGR cooler for a hydrogen fuelled SI Engine [75].

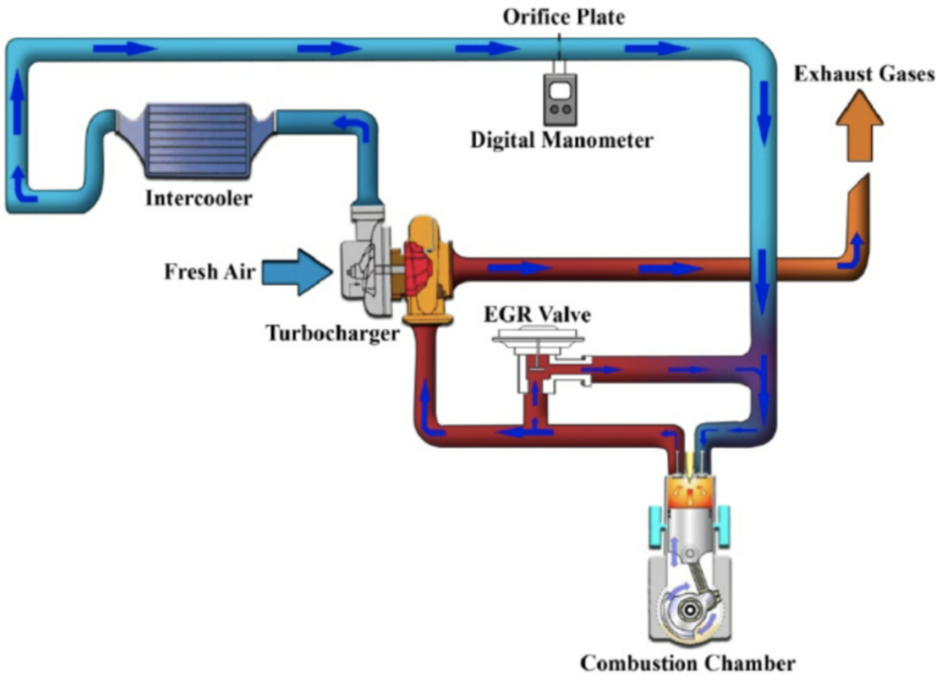


Figure 7. Schematic of using EGR with an engine [38].

To elaborate the schematic, as the exhaust gas is pushed out from the combustion chamber, a small portion is redirected and merged into the compressed intake air going into the combustion chamber. However, as the EGR valve is opened the air intake valve also needs to be closed to maintain the intake manifold pressure for proper burn [39]. This is done to dilute the air-fuel mixture. Using EGR can be an alternative to using lean burn in a hydrogen engine [43]. Although using this technique has resulted in decreased NOx emissions in gasoline or diesel engines [35], this paper will be talking about its effects on the power efficiency and NOx emissions when used with hydrogen combustion engines.

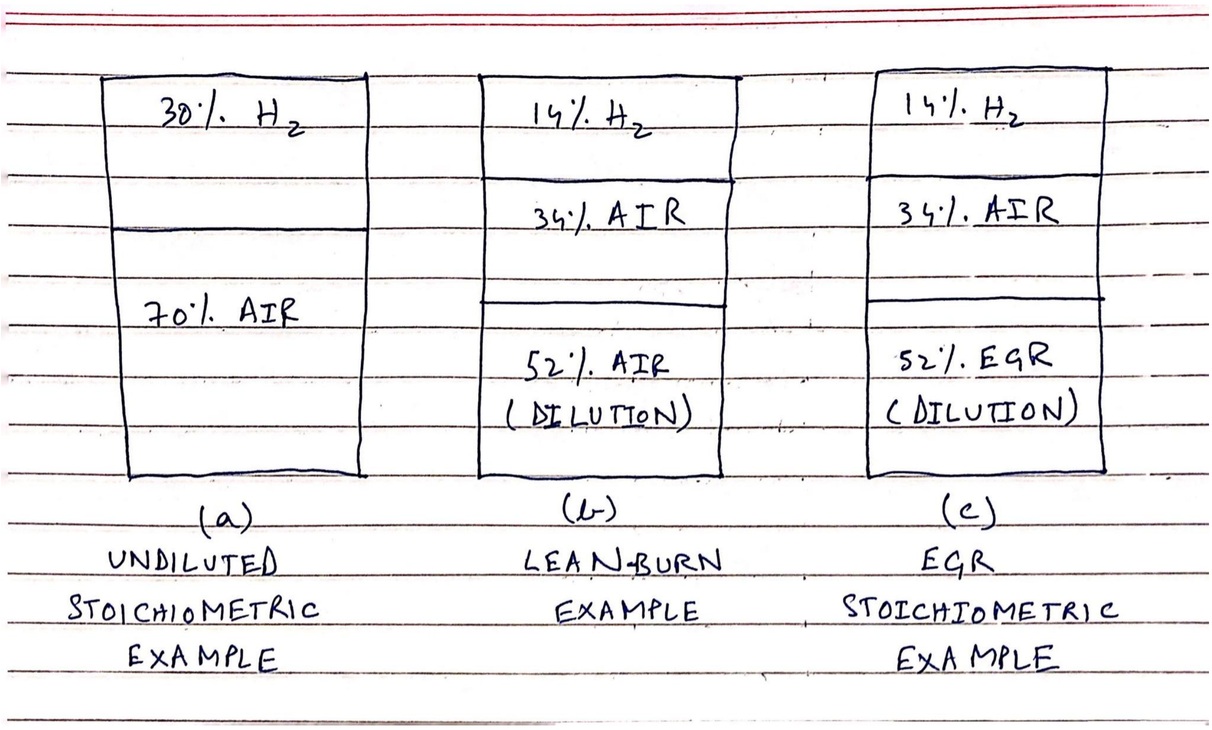


Figure 8. Examples of fuel measurement techniques. The values represented the frictional volumetric coefficients of fuel, air, and EGR [44].

Figure 8 shows a comparison between a stoichiometric engine with no additives, a lean-burn engine, and an EGR stoichiometric engine. Figure 8(a) shows how much hydrogen and air are in the combustion chamber for a stoichiometric mixture (34:1 by mass) of air and hydrogen [44]. Figure 8(b) shows how much fuel and air are in the combustion chamber when the equivalence ratio is 0.4 [44]. In this example, about half as much fuel is used as in the previous example (a). With this very lean equivalence ratio, the engine loses about half of its torque. Also, about half of the space in the combustion chamber is taken up by air that is not being used. Figure 8(c) is like the lean-burn example, but it shows how EGR works. Even though the ratio of air to fuel in this example is stoichiometric, the amounts of air and fuel in the combustion chamber are not the same as in example (a). This implies that when the mixture is combusted, the results will not be the same as in example (a). In other terms, an EGR-equipped stoichiometric hydrogen engine will produce less torque than an EGR-free stoichiometric hydrogen engine. With adequate turbocharger or supercharger boosting, the reduction in torque can be compensated for. How much less depends on the amount of EGR used.

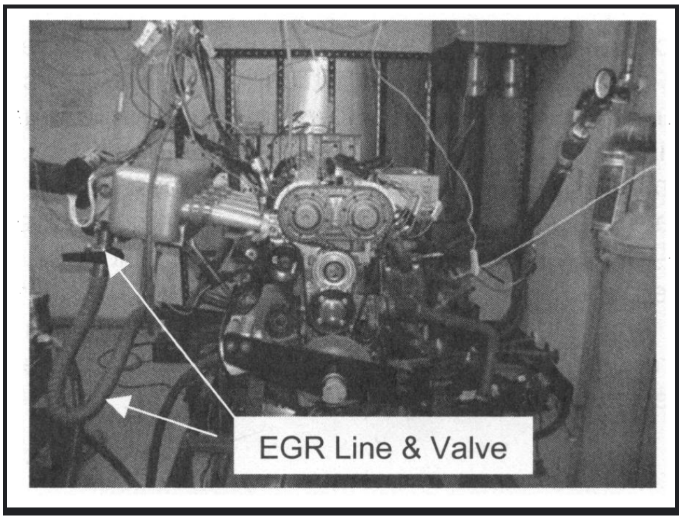
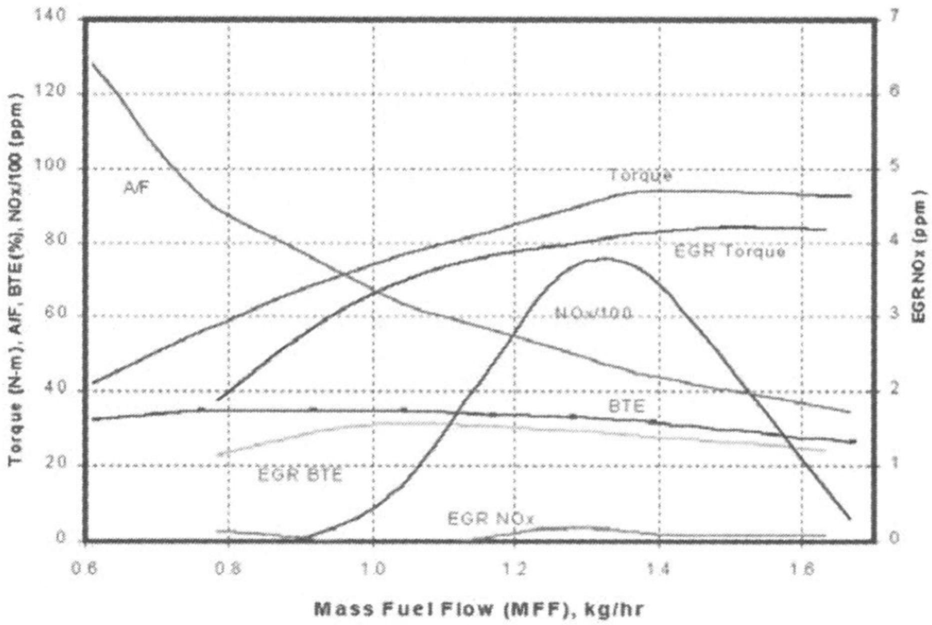


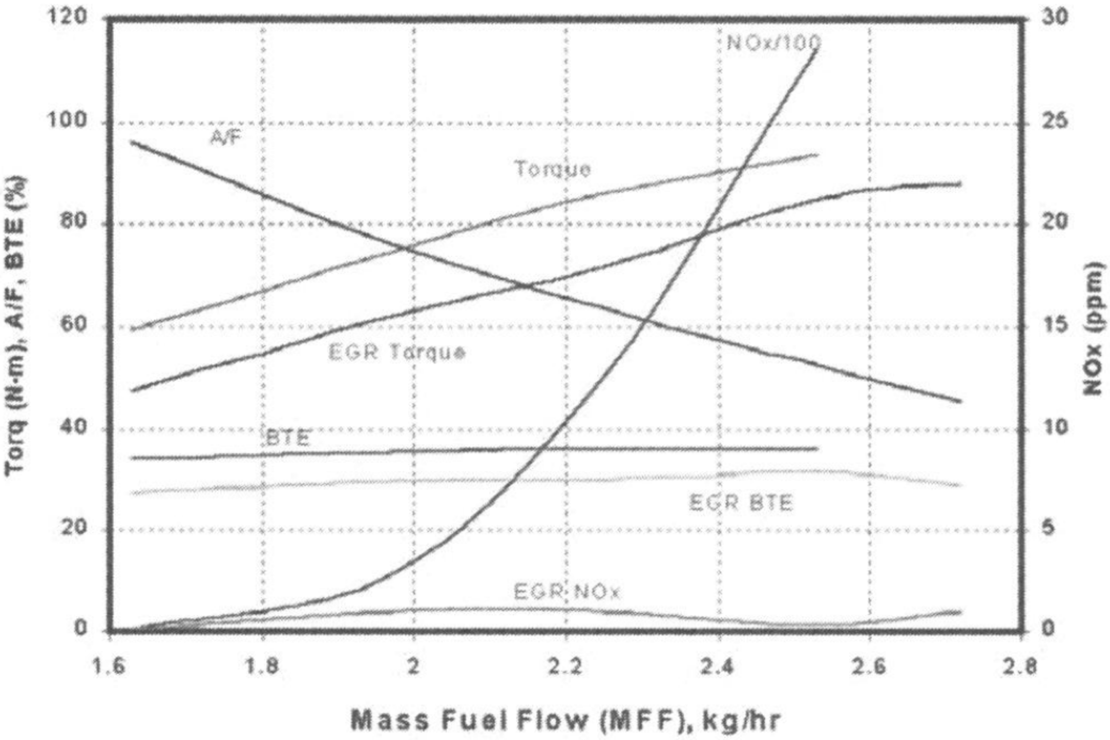
Figure 9. H_2 2.0L ZETEC Engine with EGR [39].

Natkin et al. [39] experimented using a naturally aspirated Hydrogen 2.0 L ZETEC engine at University of California-Riverside with two strategies, using no air boosting in the engine, and with using EGR. In order to minimize NOx emissions, they proposed using the engine at low load and lean burn technique (less fuel). However, this resulted in a decrease in engine torque due to less fuel being combusted. As the fuel intake increased, the NOx emissions in the naturally aspirated lean burn parameter increased as compared to using EGR [39].

Natkin et al. [39] tested out its engine at two different speeds: 1500 rpm and 3000 rpm, under lean burn and no boosting, and with EGR conditions in each speed criteria.



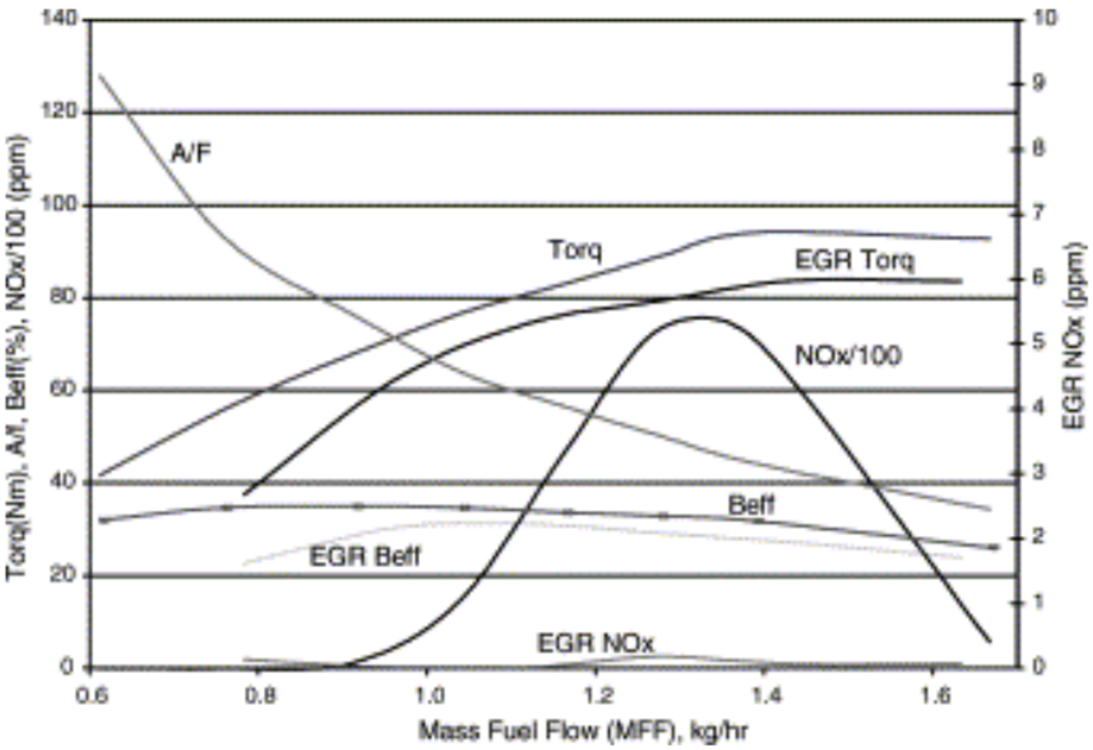
Graph 2. Emissions, Torque and efficiency data for H_2 2.0 L ZETEC engine with EGR operation at 1500 rpm [39].(EGR based data have prefixes of EGR while the ones without the prefix are the ones with data without EGR).



Graph 3. Emissions, Torque and efficiency data for H_2 2.0 L ZETEC engine with EGR operation at 3000 rpm [39]. (EGR based data have prefixes of EGR while the ones without the prefix are the ones with data without EGR).

From the two graphs, after comparing the EGR based lines with non EGR based lines, it can clearly be observed that in low loads, and lean burn condition, the power is lower when EGR is used as compared to naturally aspirated lean burn condition, along with low NOx emissions. However, as fuel flow is increased, the NOx emissions increase rapidly during lean burn in both speeds. On the other hand, when EGR is used, the NOx emissions are near zero value no matter how the fuel flow rate increases. To ensure high torque at low engine speeds, lean burn with natural aspiration is the way to go. On the contrary, if low NOx emissions are to be maintained at higher loads, EGR technology is a better option for the engine operation, only at the expense of Brake Thermal Efficiency (BTE), that is, the ratio between the engine's brake power and the fuel energy supplied to the engine and torque. However, the torque loss can be managed with more boosting, for instance, using turbochargers or superchargers.

Heffel [44] used a 4 cylinder 2.0L Ford ZETEC engine with compression ratio of 12:1, to be used with lean burn strategy. The setup was further added with a 3 way catalytic converter and an EGR valve to redirect exhaust gas into the intake manifold.



Graph 4. Engine operating parameters of FORD ZETEC hydrogen engine used by Heffel [44]. Lean burn strategy lines have no comments, whereas EGR lines do.

As it can be implied from Graph 4, EGR efficiency and torque are lower than when lean burn strategy was used. However, if NOx emissions being low is taken as a constraint, EGR seems to be a much better option than lean burn since its NOx emissions remain near zero at all fuel flow rates. It is also good to note that if a rich burn (more fuel) strategy is used, NOx emissions are lower than lean burn strategy, at the cost of lower torque generation by the engine.

Both papers suggest using part-EGR, part lean burn combustion strategy for high loads running with EGR strategy while low loads running with lean burn combustion strategy. This will be done so as to ensure low NOx emissions and higher torque and efficiency at all engine speeds [39, 44].

Regarding the problem of engine knocking and backfire, the temperature inside the combustion chamber remained around 100 degrees Celsius till an equivalence ratio of 1 (ϕ=1) for Heffel [44]. He concluded that water vapor, which was quite abundant in the exhaust after combustion, was acting as a water sprinkler system due to condensation in the intake manifold [44]. So, the problem was handled on its own to some extent.

Naganuma et al. [46] concluded that injecting fuel late in the compression stroke and igniting during the second half of injection, can reduce NOx emissions and improve thermal efficiency. With injection and ignition timings that prioritized efficiency, thermal efficiency was increased to 47%. EGR has been shown to improve efficiency and lower NOx emissions. Naganuma et al. [46] concluded that this impact is related to improved constant volume heat release and decreased cooling loss as a result of optimization at the peak heat release.

In conclusion, EGR combustion strategy is good for low NOx emissions with any fuel flow rate and engine speed at the cost of lower BTE and lower torque. On the other hand, lean burn combustion strategy is good for lower engine speeds and fuel flow rates for higher torque and efficiency.

3.2 Superchargers

A supercharger is a mechanical device utilized in internal combustion engines to force additional air into the combustion chamber, enabling the engine to consume more fuel and generate more electricity. It functions by compressing incoming air before it enters the engine, increasing air density and allowing the engine to consume more fuel during each combustion cycle.

A supercharger typically consists of a belt-driven compressor coupled to the crankshaft of the engine and an air intake system. The compressor is typically of the positive displacement or dynamic type, such as a Roots-type, screw-type, or centrifugal compressor.

The supercharger's compressor draws air from the surrounding environment, compresses it, and then forces it at a pressure greater than atmospheric pressure into the engine's intake manifold. Due to the increased air density, this results in a higher available oxygen content for combustion. Increased oxygen content enables the engine to consume more fuel, resulting in an increase in output power.

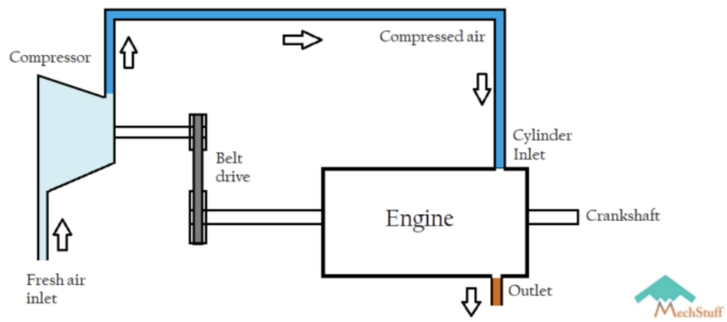


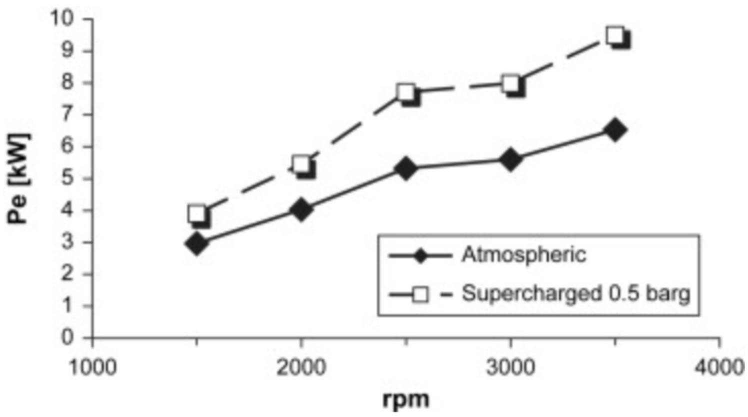
Figure 10. Basic working schematic of a supercharger [45].

Natkin et al. [39] chose a centrifugal supercharger to be used experimentally with two 2.3L Duratec HE-4 engines since roots-type superchargers were unable to attain the required 1 bar boost, whereas screw-type superchargers necessitated a more complex bypass circuit. As for thermal efficiency, the paper established that there was a loss in torque due to running of the supercharger side by side. It is also crucial to remember that by minimizing the pumping work with a technique using equivalence ratio to manage load rather than throttling, the brake thermal efficiency at the lower loads might be increased by around 15-20% [39]. The engine peaked its thermal efficiency at 50% when under throttled as compared to 37% under Wide-Open-Throttle (WOT) condition [39].

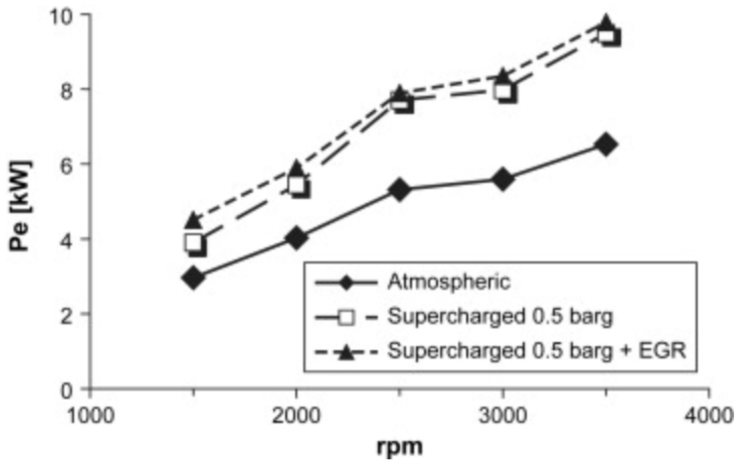
In terms of NOx emissions, at highly lean conditions and low loads, emissions were low on unburnt hydrogen and NOx. However, NOx emissions increase drastically afterwards [39].

Since the intake air temperature becomes hot due to compression, it would require to go through an air to air intercooler. In addition, the temperature had risen at low loads because the engine was throttled, which caused the air to circulate in the supercharger. This, in turn, increases the temperature. To mitigate this rise in temperature further, an additional air-conditioner to air (A/C-to-Air) intercooler was introduced using R-134a cooling medium. The paper finally suggests using supercharged boosting coupled with air to air intercooler and A/C to air intercooler while using an enrichment strategy and stoichiometric ratio being at 0.5 to match the peak torque performance of the hydrogen engine to that of a gasoline engine [39]. Nevertheless, using A/C-to-Air intercooler does not add to the increase in torque below 3000 rpm [39].

To ensure greater efficiency and reduce NOx emissions, Verhelst et al. [43] suggested using supercharging along with EGR to burn in stoichiometric conditions. The setup was made to a single cylinder two valve engine with compression ratio of 11:1. To establish vacuum at the compressor's inlet, it was found to be required to add a choke valve. This vacuum creates a flow of exhaust gasses by compensating for pressure losses in the relatively long EGR-pipe. The compressor supplies the extra energy needed to produce this vacuum [43]. Before EGR was used, running the engine at stoichiometric condition was not possible (Graph 5), but as the EGR started to be operated, not only were the stoichiometric conditions possible, but it reduced the possibility of backfire or pre-ignition events (Graph 6). This was due to the increased quantity of fuel injected and EGR rate. Main cause was due to the high heat capacity of exhaust gas along with high content of water vapor in the exhaust gas [43]. Since this research engine was one with limited volumetric efficiency, it cannot be compared to the bmep of a production gasoline engine. Compared to (atmospheric) measurements on this engine operating on methane [77], a 20% increase in power is observed; extrapolating this value yields an estimate of a 10% increase in power compared to atmospheric gasoline operation [43].



Graph 5. Brake power proportional to engine speed. WOT, atmospheric operation at stoichiometric, and supercharged operation at limited backfire/pre-ignition equivalence ratio (λ = 1.3–1.4) [43]



Graph 6. Brake power proportional to engine speed. WOT, atmospheric operation at stoichiometric; supercharged operation with EGR at stoichiometric (λ= 1); and supercharged operation at backfire/pre-ignition limited equivalence ratio (λ= 1.3-1.4) [43].

An EGR-cooler was added to maintain the inlet temperature at 50 °C in order to shield the compressor against high inlet temperatures. This is a tradeoff since it's important to maintain a high enough temperature to minimize the generation of condensation water in the compressor [43].

At the end of the exhaust system, a three-way catalyst (TWC) was included. A TWC facilitates the decrease of NOx emissions when it is operating at stoichiometry [43].

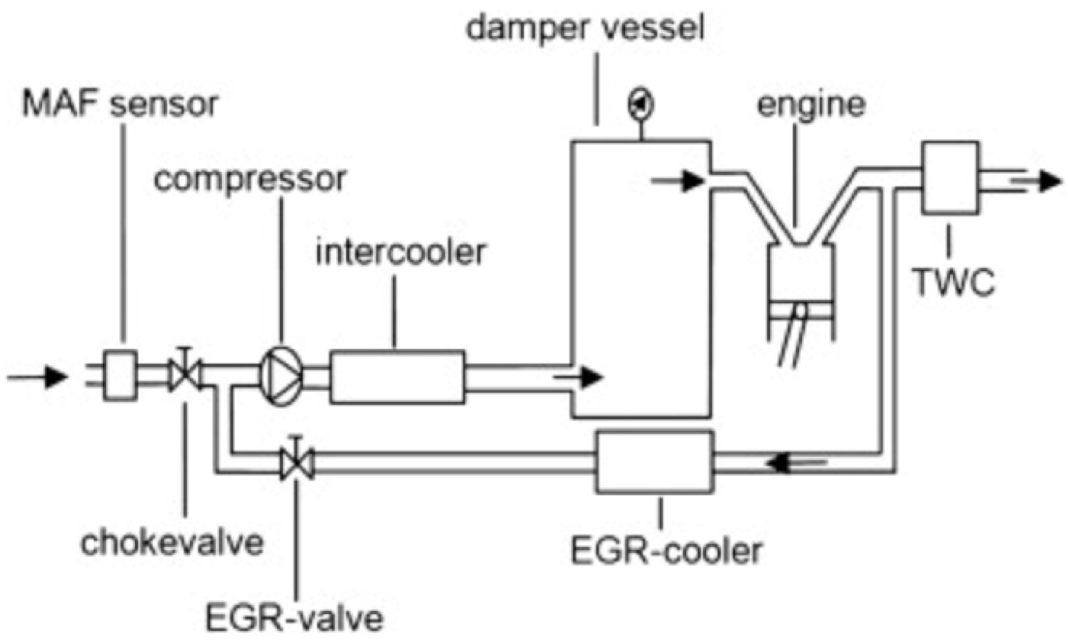


Figure 11. Experimental setup by Verhelst et al. [43].

A net 40% boost in power is produced via supercharging [43]. Given that the intercooler is big, this is a little less than what might be anticipated from the supercharging pressure, but it can still be explained because supercharging rendered stoichiometric operation impossible. Due to backfire or pre-ignition, the air to fuel equivalence ratio was now restricted to 1.3 to 1.4. In essence, this indicates that the power boost cannot be utilized due to the significant NOx emissions that will occur in an oxygen-rich atmosphere [43].

As mentioned above, the abundant water vapor content in the exhaust gas that is being recirculated in the intake manifold, enables usage for more fuel flow rates without any pre-ignition or backfire by maintaining low temperatures [43]. Due to this, sufficient NOx treatment is possible along with a 50% increase in net power. Since, the temperature in the combustion chamber was lower, therefore less NOx particles were formed [43].

To limit cylinder peak temperature and NOx formation, the EGR percentage rises with increasing charging pressure, reaching a maximum of 45.9% at 1 barg [43]. Similar to lean operation, the brake torque increases when the charging pressure is increased. At atmospheric pressure, the braking torque is 12.3 Nm (brake mean effective pressure (bmep) = 3.85 bar), and the EGR rate is approximately 37%. At 1 barg, the maximum torque of 22.6 Nm is attained (bmep = 7.08 bar). Supercharging in conjunction with EGR results in an 84.7% increase in output over atmospheric operation ($\lambda = 1$) [43].

In 2009, Verhelst et al. [63], introduced a GM 7.4L V8 supercharged hydrogen internal combustion engine that was found to have 60% higher torque than the naturally aspirated version of the same hydrogen engine.

It can be observed from all arguments regarding supercharged boosting in a hydrogen fuelled IC engine, low loads with lean burn strategy is good for high torque and low NOx emissions. Nevertheless, to increase torque but keep NOx emissions on the lower side, EGR needs to be used with supercharging in order to enable burn in stoichiometric conditions.

3.3 Turbochargers

Internal combustion engines generally use turbochargers as mechanical components to boost power and improve efficiency by pushing more air into the combustion chamber. They typically have a turbine and a compressor that share a similar shaft and are rotated by the engine's exhaust gasses.

The following are characteristics of a turbocharger:

The turbine, which has either radial or axial flow, is powered by the engine's exhaust gasses. It uses the energy from the exhaust fumes to operate the compressor and is attached to the exhaust manifold. A turbine typically consists of a wheel with several blades, which revolve as a result of the flow of exhaust gasses over them.

Typically, a centrifugal compressor propelled by a turbine serves as the compressor. It draws in and compresses ambient air before sending it to the engine's intake manifold. The compressed air is forced into the engine's combustion chamber, allowing for a greater amount of air to be merged with the fuel for combustion, thereby increasing the engine's power output. Turbochargers require high-speed rotation of the turbine and compressor wheels.

Numerous turbochargers feature a wastegate, which is a valve that regulates the amount of exhaust gas passage through the turbine. The wastegate assists in regulating turbine speed and preventing engine damage caused by over-boost.

Sometimes an intercooler is used to cool down the compressed air before it enters the engine's intake manifold in turbocharged engines. This, in turn, reduces the temperature of the compressed air, increasing its density which allows more air to be packed into the combustion chamber, thereby increasing engine efficiency.

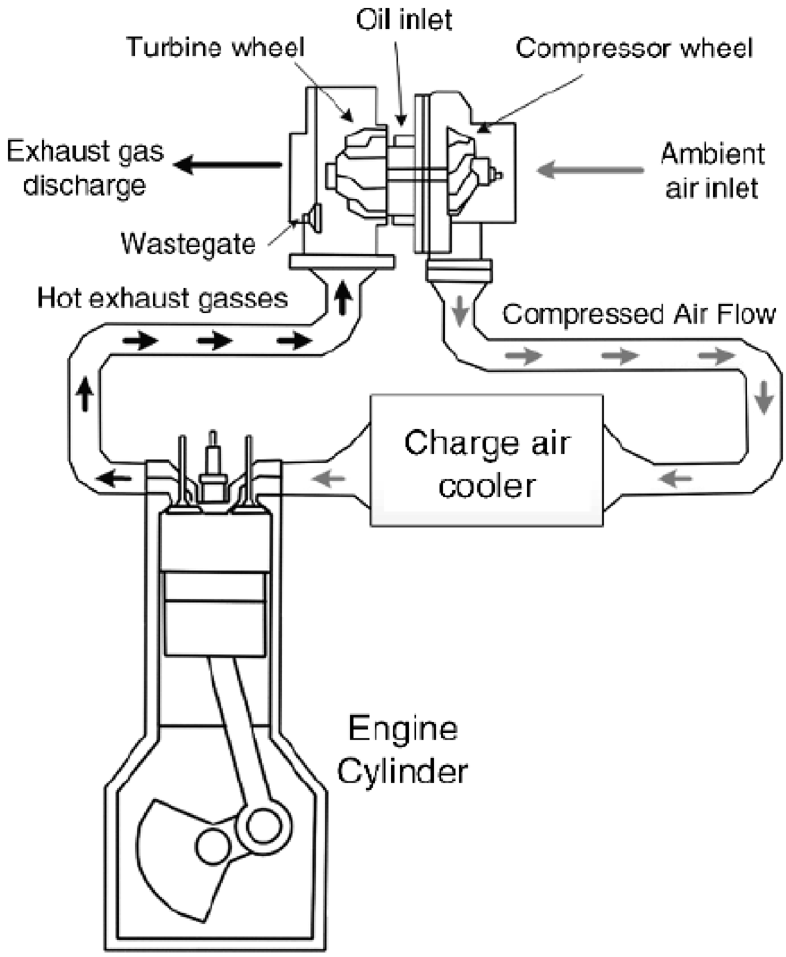
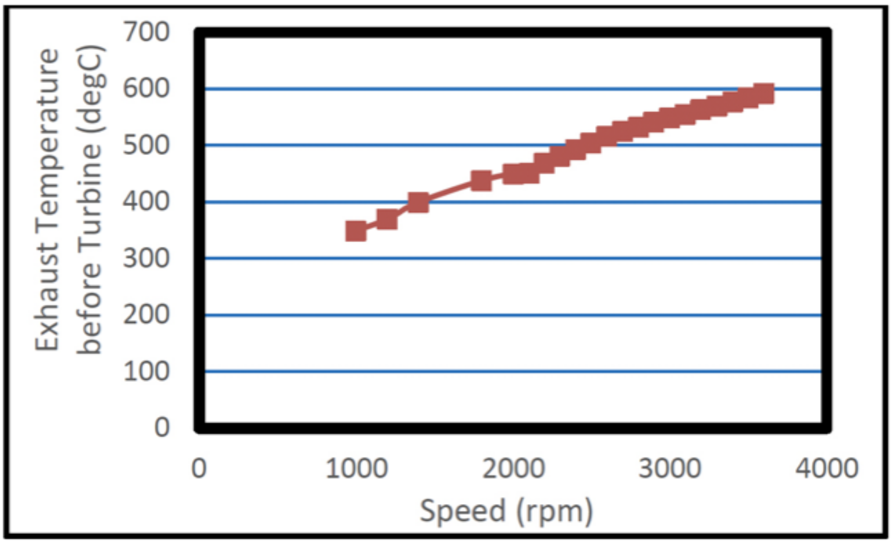


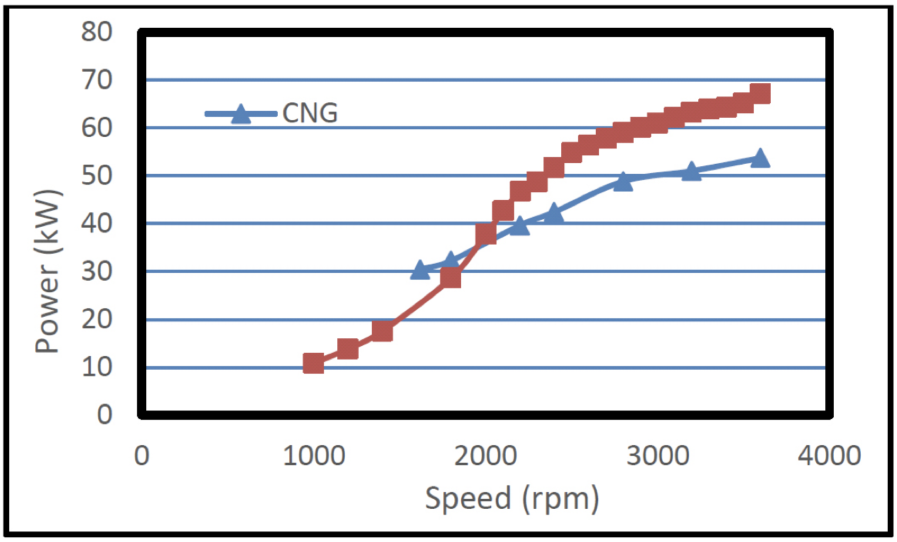
Figure 12. Basic working schematic of a turbocharger [47].

Jilarakara et al. [68] used a base of 4 cylinder naturally aspirated CNG (Compressed Natural Gas) engine and then changed the engine to a turbocharged hydrogen combustion engine by using the methods as mentioned above in Section 2.1. The compression ratio was found to be 12:1 for the changed hydrogen engine. The injection system was developed as a timed manifold injection system, that is, the hydrogen fuel will be injected after the intake is opened. This avoided backfire or pre-ignition and the initial introduction of air diluted any remaining heated gasses and cooled any potential hot spots [68]. The equivalence ratio used for the experiment was 0.5-0.6 to ensure low NOx emissions which was measured with the help of a dynamometer. The boost pressure was found to be 2.4 at 3600 rpm for the hydrogen engine.

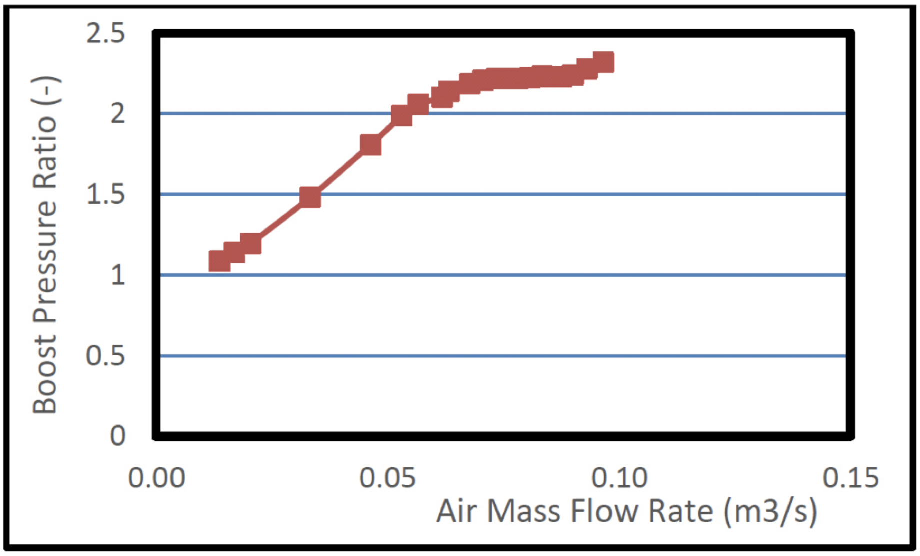
The paper concluded that below 2000 rpm the torque generated by the boosted hydrogen engine was lower than that produced by the base engine at the same speed [68]. At 3600 rpm, the exhaust temperature was found to be 873.16K, in comparison to 723.16K at engine speeds below 2000 rpm. The low exhaust temperature was not sufficient to create enough boost pressure [68]. However, at 2000 rpm and 3600 rpm, the torque and power generated by the boosted hydrogen engine was greater than that of the base engine [68] since the exhaust temperature increased enough to create sufficient boost pressure. To increase the power generated by the hydrogen engine below 2000 rpm, the equivalence ratio was increased to 0.6 [68]. With this, the power increased from 12kW to 14kW at 1200 rpm. Further increase in equivalence ratio was observed to have more NOx emissions and possibility for backfire [68]. The boost pressure of 2.4 at 3600 rpm of the hydrogen engine due to turbo boosting ensured more power to be delivered. Due to quicker combustion of hydrogen (higher flame velocity), the reduced heat loss in the combustion chamber enabled the engine to have brake thermal efficiency (BTE) to be 38% and 30%+ at 2000 rpm and 3600 rpm, respectively [68]. By the virtue of leaner equivalence ratio throughout the process low NOx emissions were discovered.



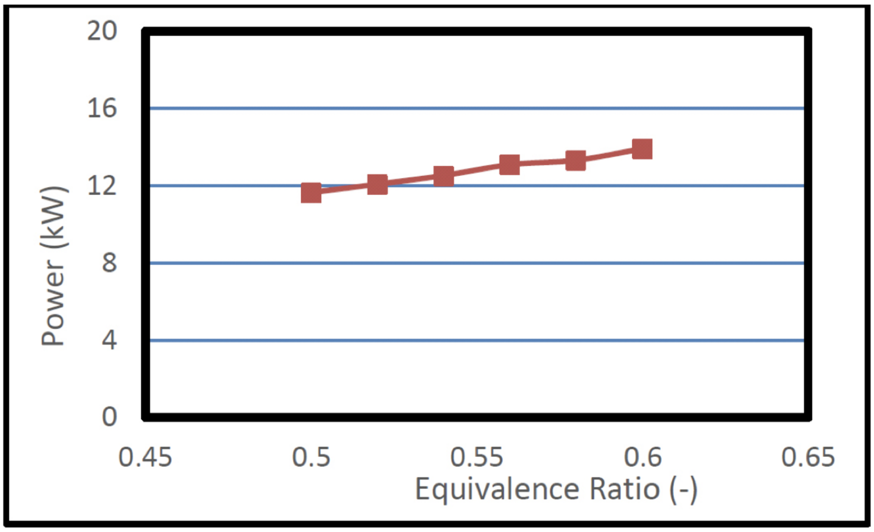
Graph 7. Exhaust Gas Temperature vs engine speed of Hydrogen Engine [68].



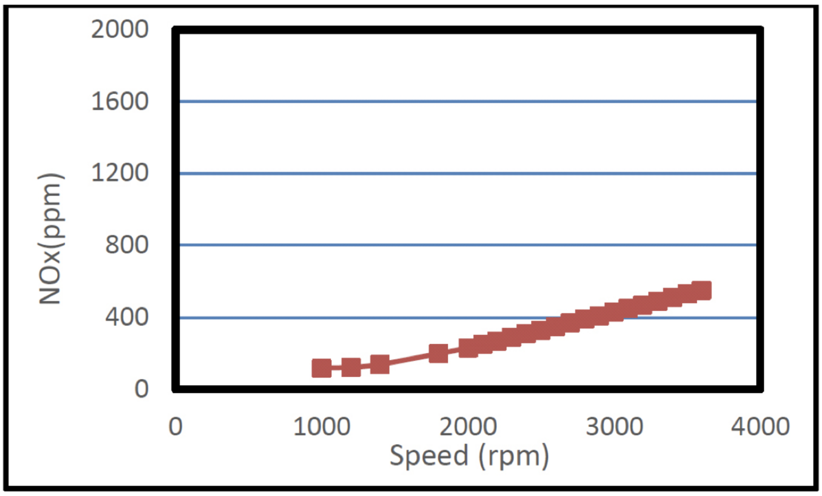
Graph 8 . Power vs Speed comparison of base engine with hydrogen engine [68]. (The red line is plot for when hydrogen was used while blue is for CNG.



Graph 9. Boost pressure ratio vs Air Mass flow rate of hydrogen engine [68]. The red dots are for when hydrogen fuel was used.

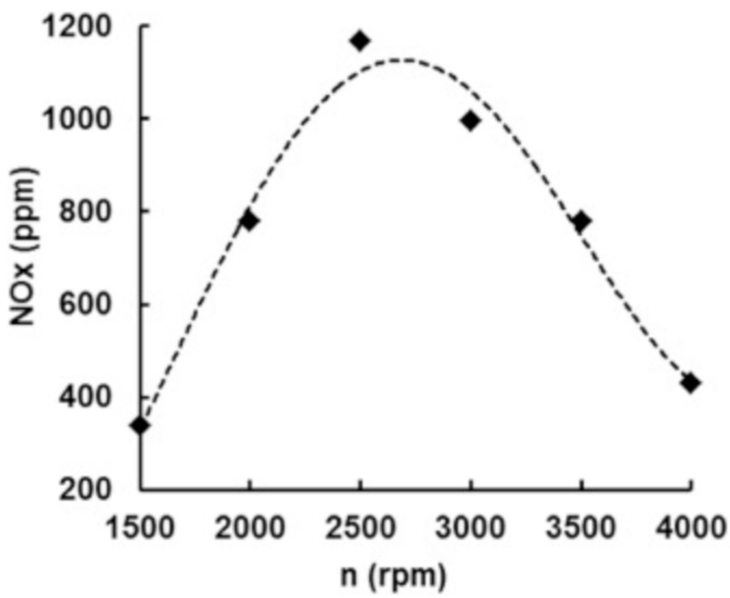


Graph 10. Power vs Equivalence ratio for hydrogen engine [68].

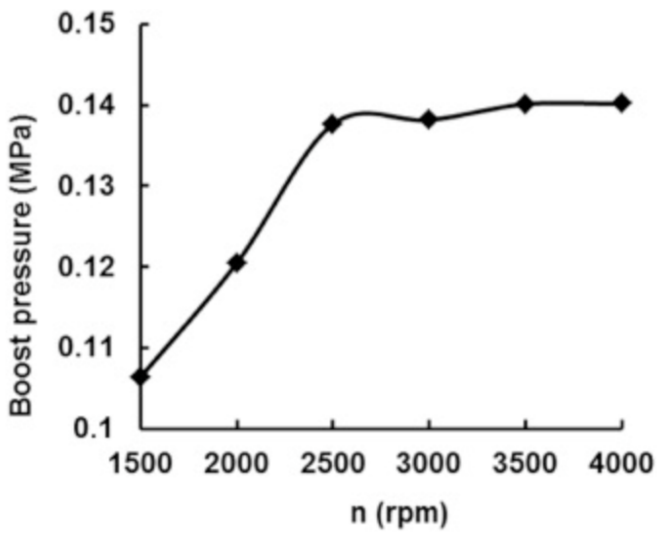


Graph 11. NOx emissions vs Engine speed for hydrogen engine [68].

Luo et al. [62] experimented with a converted 2.3 L, 4 stroke, PFI engine from gasoline to hydrogen combustion with compression ratio 9.3 with equivalence ratio (λ) ranging between 0.4-1.1. The setup included an intercooler system for the compressed air to cool down and an oil and water cooling system along with a CW250 eddy current dynamometer keeping at wide open throttle (WOT) position [62]. They observed that as the engine speeds increased, the compression temperature also increased, thereby adding to high NOx emissions (as much as 1200 ppm at 2500 rpm). On further increase in engine speed, it was noted that the time required for nitrogen to burn and form NOx was decreased and hence, the nOx emissions decreased after 2500 rpm engine speed (λ=0.55) [62]. Due to the constraint of the injection pressure of the nozzle, the mass flow rate of hydrogen injection is insufficient, resulting in a decrease in the equivalence ratio as the engine speed increases, which is the cause of the decrease in NOx emissions [62]. When the BMEP increases from 0.27 MPa to 0.69 MPa, the rate of NOx emission growth remains sluggish. There are two possible reasons. On one hand, the increase in the energy of the exhaust gasses increases the boost pressure. The boost pressure increases the pressure at the conclusion of the compression stroke, which raises the temperature of the combustion [62]. While on the other hand, since NOx formation follows the Zeldovich mechanism, the amount of NOx produced increases exponentially as the combustion temperature rises, thanks to the energy provided by the rising temperature. The result is that the NOx emission initially exhibits a sluggish trend and then accelerates in the subsequent period [62].



Graph 12. NOx emissions vs engine speeds for a turbocharged hydrogen engine [62].



Graph 13. Boost pressure vs engine speed [62].

Bao et al. [71] said that with the aid of EGR and lean mixture combustion, NOx emissions are significantly reduced while maintaining the same load and thermal efficiency. Increasing the compression ratio and installing a turbocharger triples the brake mean effective pressure (BMEP) and improves the engine's efficiency by about 10 percent, which are proven to be essential for achieving near-zero emissions. However, the trade-off relationships between power, efficiency, and NOx emissions hold true when maximizing power and efficiency. NOx emission must be sacrificed in order to reach the target of 42% BTE and 20 bar BMEP. To accomplish near-zero NOx emissions under all working conditions, a series of NOx after-treatment systems must be implemented [71]. The BMEP of a naturally aspirated engine is only 4.7 bar (0.47 MPa), but with the use of a proper turbocharger and 16 MPa injection pressure, the output is increased over 2.5 times, reaching 12.1 bar (1.21 MPa). The brake thermal efficiency has also increased significantly, from 30% to 40.4%, an increase of 10.4% [71].

Munshi, S. R. [69] observed that a study conducted on a turbocharged lean-burn SI engine operating on natural gas as well as mixtures of hydrogen and natural gas (20/80 and 30/70 H_2/natural gas by vol%) revealed that it is possible to reduce NOx and total hydrocarbons (THC) emissions without sacrificing engine torque or fuel economy [69].

All in all, turbochargers when used in hydrogen combustion engines are required to work at extreme lean burn conditions with equivalence ratio till 0.6 in order to control NOx emissions. Furthermore, using EGR can help deal with engine backfire or knocking by reducing the temperature in the chamber with the help of abundant water vapor in the exhaust gas [71]. The power delivered by a turbo boosted engine is far more than that delivered by a naturally aspirated engine. Higher power is generated at high engine speeds due to lack of exhaust gas temperatures at low speeds [68] or resistance from compressor turbine at low speeds [62].

Specificities into what changes we need to make to a turbocharger in order to use it with a hydrogen combustion engine haven't been discussed in the papers reviewed. Considerable amount of research is required to compare the boost pressure in gasoline, diesel and hydrogen engines due to differences in the basic parameters of the engines used by the studies.

4 Conclusion

Hydrogen is a viable alternative fuel for combustion in an internal combustion engine because of its wide flammability, high flame velocity, and no carbon emissions when burnt. Even though using hydrogen as a combustible fuel has its benefits, there are its drawbacks as well. One major concern with using hydrogen in an ICE is the possibility of abnormal combustion like knocking and backfire or pre-ignition or auto-ignition. One other concern is the generation of NOx emissions which are considered to be greenhouse gasses [62]. In order to face these problems, different fuel injection systems, air boosting strategies and load strategies must be implemented.

Direct (DI) or Dual Injection systems seem more viable as compared to port fuel injection systems due to the possibility of knock or backfire in the case of PFI. DI also has the possibility of facing problems at high speeds due to increased pressure and temperature in the chamber. Dual injector systems enable the use of direct injection at low engine speeds and PFI at high engine speeds [67].

Using EGR to dilute the intake air is a good method to control low NOx emissions during all engine speeds, but this comes at the cost of low brake thermal efficiency (BTE) and low torque. However during rapid turbulent combustion, temperatures run high due to high auto-ignition temperature of hydrogen. To fight this, the EGR rate is increased in order to curb NOx emissions that run high due to increased combustion temperature. Using a Three way catalyst (TWC) in the later stages of the exhaust system to treat the emissions is helpful in decreasing NOx emissions. EGR reduces the occurrence of knock or backfire or pre-ignition due to the presence of abundant water vapor in the recirculated exhaust gas, which works like a water sprinkling system, thereby decreasing the chamber temperature [43]. Since, hydrogen engines run at higher temperatures due to its higher auto-ignition temperatures than normal conventional engines, more EGR might be required to reduce the temperature in the combustion chamber such that less NOx emissions are released. Due to the addition of a TWC, NOx emissions can be curbed further.

Turbocharging a hydrogen internal combustion engine (HICE) needs to be at low equivalence ratios, that is, high lean-burn condition, especially at low speeds. This, in turn, causes low torque to be generated at low speeds. Nevertheless, as engine speed picks up, the torque generated increases as well, along with an increase in NOx emissions. The emissions then start reducing due to lack of time of combustion of nitrogen in the air at high speeds. Using EGR with turbochargers in an engine [71] looks good since power and torque are increased while keeping the same low NOx emissions condition as constraints. This results in a higher BTE.

Supercharging in a HICE increases the boost power generated by the engine as compared to its naturally aspirated counterpart. Although the boosting done by supercharging is good, it results in lower torque if compared with a gasolene engine of the same type. After using an air to air intercooler, an A/C to air intercooler coupled with stoichiometric ratio of 0.5 and using an enrichment strategy, can the supercharged engine's BTE be comparable to that of a gasoline engine [39]. To further deal with NOx emissions, EGR has to be used with an EGR valve and a three way catalyst (TWC) [43].

Air boosting has a lot of perks and drawbacks to be used in a hydrogen fuelled internal combustion engine. However, those drawbacks can be dealt with by using the right strategies.

5 Way Forward

Although sufficient research has already been done in areas regarding the usage of hydrogen as a fuel for combustion in an internal combustion engine, there is yet to discover and invent or improve many more strategies and technology for higher BTE, power and torque, and to reduce NOx emissions.

Using hydrogen in an ICE does not require high purities of hydrogen, different methods to incorporate hydrogen should be researched upon. Comotti et al. [72] researched upon using ammonia as a fuel to generate hydrogen in an ICE. Yet, the increase in NOx emissions has been imminent. Further research into solving the problems faced will be done.

Incorporating different load strategies and injection strategies together along with the air boosting technologies is required for a more comprehensive understanding of hydrogen as a fuel in an ICE.

It has been reviewed many times on the effects of using hydrogen as a bi-fuel with diesel or LPG or natural gas or gasoline in past papers [22, 31, 34]. Comprehending their use with different parameters and strategies is needed in the future for better use of resources in the future.

A more comparative analysis on the air boosting technologies is required, preferably using the same engine type such that all the basic parameters regarding the engine except the air boosting strategy being used remains the same. This would help a more generic comparison between the strategies to make it clear what operation will be the best for the future.

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